Impact assessment of energy-efficient lighting interventions

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DECLARATION

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Abstract

Energy-efficient (EE) lighting projects form a substantial percentage of Demand Side Management (DSM) initiatives. These largely entail the exchange of one lighting technology for another more energy-efficient lighting technology. The DSM process typically involves a proposal from an Energy Services Company (ESCO) to retrofit an existing lighting technology with another on the property of a third party, the client. For scoping purposes, ESCOs perform energy savings calculations based on information obtained from the datasheets of the relevant lighting technologies. Such datasheet specifications rarely incorporate the effects of supply voltage fluctuations on energy consumption, which can impact on the accuracy of the savings calculations. Furthermore, modern EE lighting technologies such as Compact Fluorescent lamps (CFLs) employ power electronic circuitry that can in principle give rise to Quality of Supply (QoS) problems such as harmonic distortion. The usage profiles of artificial light fittings targeted in DSM interventions represent another important factor in determining the savings impacts of such projects. There is currently limited information on methodologies for obtaining such usage profiles. In practice, the scoping and impact verification of EE lighting projects are conducted using project-specific applications and spreadsheets that are time-consuming and error-prone.

In view of the above-mentioned considerations, this investigation aims to address the lack of voltage-dependent energy consumption data and QoS impacts by conducting a laboratory investigation for all relevant lighting technologies, namely incandescent lamps, CFLs, tubular fluorescent lamps and high intensity discharge lamps. Appropriate mathematical models for the voltage-dependent energy consumption characteristics of these light technologies are derived from the measurements. The supply current harmonic distortion associated with the various lamp types are investigated, particularly with regard to neutral current loading caused by zero-sequence harmonics. Methodologies for obtaining accurate and reliable light usage data using commercially available data loggers are reviewed. A database structure is subsequently designed and implemented to store the information relevant for impact assessment, including the mathematical models of energy consumption, supply voltage profiles and light usage profiles.

Finally, an Integrated Software Program (ISP) is developed to implement a methodology for assessing the savings impacts of practical EE lighting projects, using the database as the main input source. The ISP is tested by implementing a real case study. It is shown that the ISP yields accurate results for the case study considered in the evaluation.

Opsomming

Energiedoeltreffende (ED) beligtingsprojekte vorm ’n wesenlike persentasie van vraagkantbestuur (VKB) inisiatiewe. Dit het grootliks te doen met die vervanging van een beligtingstegnologie met ’n ander meer energiedoeltreffende beligtingstegnologie. Die VKB proses behels normaalweg ’n voorstel van Energie Dienste Maatskappy (EDM) om ’n bestaande beligtingstegnologie te vervang met ’n ander op die perseel van ’n derde party, die kliënt. EDMs doen energiebesparingsberekeninge op grond van tegniese inligting wat vanaf die datablaaie van die betrokke beligtingstegnologieë verkry word. Hierdie datablad spesifikasies maak selde voorsiening vir die uitwerking van toevoerspanningfluktuasies op energieverbruik, wat die akkuraatheid van die besparingsberekeninge kan beïnvloed. Moderne ED beligtingstegnologieë soos kompakte fluoresseerlampe maak verder gebruik van drywingselektronika stroombane wat in beginsel kan lei tot kwaliteit van toevoer (KVT) probleme soos harmoniese distorsie. Die gebruiksprofiele van kunsmatige lig verteenwoordig nog ’n belangrike faktor wat die besparingsimpakte van VKB projekte bepaal. Daar is tans beperkte informasie oor die metodologie om sulke gebruiksprofiele te verkry. In die praktyk word die verifiëring van die impak van ED beligtingsprojekte gedoen deur gebruik te maak van projekspesifieke programme en sigblaaie wat tydrowend is en geneig is om te lei tot foute.

In die lig van die bogenoemde oorwegings, streef hierdie ondersoek om die tekort aan spanningsafhanklike energieverbruiksdata en KVT impakte te aan te spreek deur ‘n laboratorium ondersoek uit te voer vir al die relevante beligtingstegnologieë, naamlik filament lampe, kompakte fluoresseerlampe, buisvormige fluoresseerlampe en hoë-intensiteit ontladingslampe. Gepaste wiskundige modelle vir die spanningsafhanklikeenergieverbruik eienskappe van hierdie beligtingstegnologieë word vanuit die metings afgelei. Die harmoniese vervorming van die toevoerstroom van die verskillende beligtingstegnologieë word ondersoek, veral met verwysing tot neutraalstroombelasting wat veroorsaak word deur zero volgorde harmoniese ordes. Metodologieë vir die verkryging van akkurate en betroubare ligverbruikprofiele deur die gebruik van komersieel beskikbare dataversamelaars is nagegaan. ’n Databasis struktuur is vervolgens ontwerp en geïmplementeer om die toepaslike inligting vir bepaling van die impakte te stoor, insluitend die wiskundige modelle vir energieverbruik, toevoerspanning-en ligverbruikprofiele.

’n Geïntegreerdesagtewareprogram (GSP) is ontwerp om die metodologie vir die bepaling van besparingsimpakte van praktiese ED beligtingsprojekte te implimenteer, deur gebruik te maak die databasis as die hoofbron van insette. Die GSP is getoets deur ’n werklike gevallestudie te implimenteer. Daar is bewys dat die GSP akkurate resultate lewer vir die gevallestudie wat in die evaluering gebruik is.

Acknowledgements

I would like to thank Prof HJ Vermeulen, Department of Electrical and Electronics Engineering, University of Stellenbosch, for his invaluable contribution to this project. I would also like to thank the members of Stellenbosch Measurement and Verification for their input and assistance during this project. Finally, I would like to thank my family and friends for their support and encouragement.

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Abbreviations and Symbols

c	cent
CFL	Compact Fluorescent Lamp
CO_2	Carbon dioxide
CTAD	Corporate Technical Audit Department
DSM	Demand side management
ESCO	Energy Service Company
FEMP	Federal energy management projects
IPMVP	International performance measurement and verification protocol
H_2O	Water
HIDL	High Intensity Discharge Lamp
IL	Incandescent Lamp
ISP	Integrated Software Program
kg	kilogram
kl	kilolitre
kVA	kilovolt-ampère
kW	kilowatt
kWh	kilowatt-hour
LUP	Artificial-light Usage Profile
M&E	Monitoring and evaluation
M&V	Measurement and Verification
MW	Megawatt
MWh	Megawatt-hour
NMD	Notified Maximum Demand
R	Rand
T&E	Tracking and evaluating
TFL	Tubular Fluorescent Lamp
TOU	Time of Use

1. Project Overview

1.1 Project motivation

Energy-efficient (EE) lighting projects form a substantial percentage of Demand Side Management (DSM) initiatives. This largely entails the exchange of one lighting technology for another, more energy-efficient, lighting technology. The typical EE lighting DSM intervention involves an Energy Services Company (ESCO) that propose to retrofit a certain lighting technology with another on the property of a third party, i.e. the client.

ESCOs make their energy saving calculations based on technical information obtained from site surveys and the datasheets of these lighting technologies. The information on these datasheets, however, rarely allows for the effects of supply voltage fluctuations on the energy consumption of the certain lighting technologies involved. Energy savings calculations must also take into consideration the frequency of use of the artificial lighting. As yet, there is no accurate data or method of obtaining the data on the usage of artificial light for a certain property. This lack of comprehensive and reliable data can lead to conflict between the ESCO and the party assigned to do the Measurement and Verification (M & V) of the projects.

In view of the above considerations, this project aims to develop an improved methodology for assessing the savings associated with an energy–efficient lighting project. This methodology must take cognizance of the following:

- The methodology must incorporate accurate and reliable light usage data for industrial, commercial and residential projects.
- Utilize mathematical models of the different lighting technologies to predict the energy consumption of these technologies based on its supply voltage.
- Be supported by an integrated software program (ISP) with database capabilities.

The effect on the quality of supply of the network is also of concern.

1.2 Project description

1.2.1 Overview

This project aims to improve the current deficiencies in the M&V of EE lighting projects. This is to be achieved by researching and developing the following key areas:

- Measuring and modelling the voltage-dependency of the energy consumption of the applicable lighting technologies. In order to do this, it is necessary to properly identify the types of lighting technologies to be targeted.
- Investigate methodologies for measuring or otherwise obtaining Light Usage Profiles (LUP).
- Developing and implementing a versatile methodology for accurately assessing the savings of EE lighting projects through an Integrated Software Program.

The research data is to be incorporated into an Integrated Software Program (ISP) that will function as a tool for performing scoping and M & V performance assessments for DSM EE lighting projects.

1.2.2 Modelling the voltage-dependent energy consumption of relevant lighting technologies

1.2.2.1 Lighting technologies targeted in the investigation

The lighting technologies to be targeted in this investigation are those that are most commonly used for spatial lighting, and exclude those used for decorative purposes, ie. neon advertisements. EE lighting projects and the associated lighting technologies can be classified according to the applicable load sector, which can broadly be categorized as industrial, commercial and residential sectors. For the purpose of this investigation these sectors can be defined as follows:

- *Industrial sector:*

  The industrial sector can be loosely defined as consisting of the following trades:

  - Manufacturing.
  - Construction.
  - Mining.
  - Agriculture.

  In this sector spatial lighting generally consists of High-intensity Discharge Lamps (HIDLs) and Tubular Fluorescent Lamps (TFLs) as they emit a larger amount of light per unit package area than incandescent lamps and Compact Fluorescent Lamps (CFLs).

Energy saving initiatives generally involves replacing HIDLs with TFLs and replacing the magnetic ballasts of existing TFLs with electronic ballasts.

The artificial-light usage in this sector is likely to be cyclical to a large extent as light usage is based on procedure rather than the state of natural light, i.e. in production areas lights are turned on when production starts and they are turned off when production stops.

- *Commercial sector*:

  The commercial sector can be generally defined as consisting of the following:

  - Non-manufacturing businesses.
  - Hotels.
  - Restaurants.
  - Wholesale businesses.
  - Retail stores.
  - Health, social and educational institutions.

  This sector contains a mix of the lighting technologies relevant to this project. Usage profiles of certain sub-divisions of this sector can be cyclical such as retail stores who turn their lights on when the store opens and turns it off when the store closes. As a result of the variety of trades in this sector, some usage profiles are likely to be local to certain trades only. Artificial light usage based on the state of natural light is likely to be relevant to certain divisions in this sector and irrelevant to other divisions.

- *Residential sector:*

  The residential sector consists of living quarters for private households. The main lighting technology used in this sector is incandescent lamps although this might be changing to CFLs. The usage profile for this sector is likely to be heavily dependant on the state of natural light. It is also likely to be the least cyclical of the three sectors, as lights are likely to be turned on and off as certain rooms are used. The frequency of use of certain rooms is likely to impact on the usage profile.

Based on the above review, the following lighting technologies will be targeted in this research project:

- Incandescent lamps (ILs)
- Compact fluorescents lamps (CFLs).
- Tubular Fluorescents Lamps (TFLs) with magnetic and/or electronic ballasts.
- High Intensity Discharge (HID) lamps.

The measurements necessary to determine and model the energy consumption of the relevant lighting technologies are as follows:

- RMS Voltage and voltage waveform data
- RMS Current and current waveform data

- Active power consumption
- Reactive power consumption
- Apparent power consumption
- Power factor

This combination of measurements makes it possible to accurately model any of the relevant lighting technologies.

1.2.2.2 Energy consumption modelling

The main aim of EE lighting projects is to reduce the energy consumption in kilowatt-hours (kWh) used by spatial lighting by replacing the existing technology with a more energy-efficient technology. Modelling of the real power consumption of the lighting load before and after the intervention is often the main approach that is used for the savings calculations. The aim of modelling the energy consumption of the relevant lighting technologies is to predict the energy consumption for a given supply voltage, thereby making the energy savings calculation more accurate if a voltage profile is available. The modelling is done by making use of polynomial curve fitting, with the measured supply voltage data as input parameter.

The national energy supplier of South Africa, Eskom, specifies that the voltage that it supplies is guaranteed to always be between -10% and +10% of their nominal voltage of 230V [1]. Therefore, the energy consumption of the lighting technologies will be measured and modelled for this range, i.e. 207V to 253V.

1.2.3 Light usage profiles

Artificial light usage profiles (usage profiles) form an integral part of energy savings calculations in EE lighting projects. Previous methods for obtaining usage profiles have required information supplied by the client. This results in inaccuracy and a lack of scientific validity. The viability of using the "Hobo® U9-002 light on/off data logger" as light usage logging equipment for the three load sectors will therfore be investigated.

1.2.4 Integrated software program functionality and specifications

The Integrated Software Program (ISP) has two main functions. It serves as a database containing the following data:

- Technical information of the different lighting technologies, i.e.

    - Part names.
    - Operating voltages and corresponding currents.
    - Power outputs.
    - Physical information.
    - Operating temperature ranges.
    - Mathematical models.
- Voltage profiles
- Artificial light usage profiles

The ISP can also be used to calculate the half-hourly active energy demand, as a result of artificial spatial lighting, of any site given the necessary input information. The ISP is able to generate the following output data:

- Half hourly active energy usage, of relevant lighting technologies, over a user defined period.
- Information pertaining to the project case.

1.3 Project overview diagram

Figure 1 shows a block diagram depicting the various components of this project.

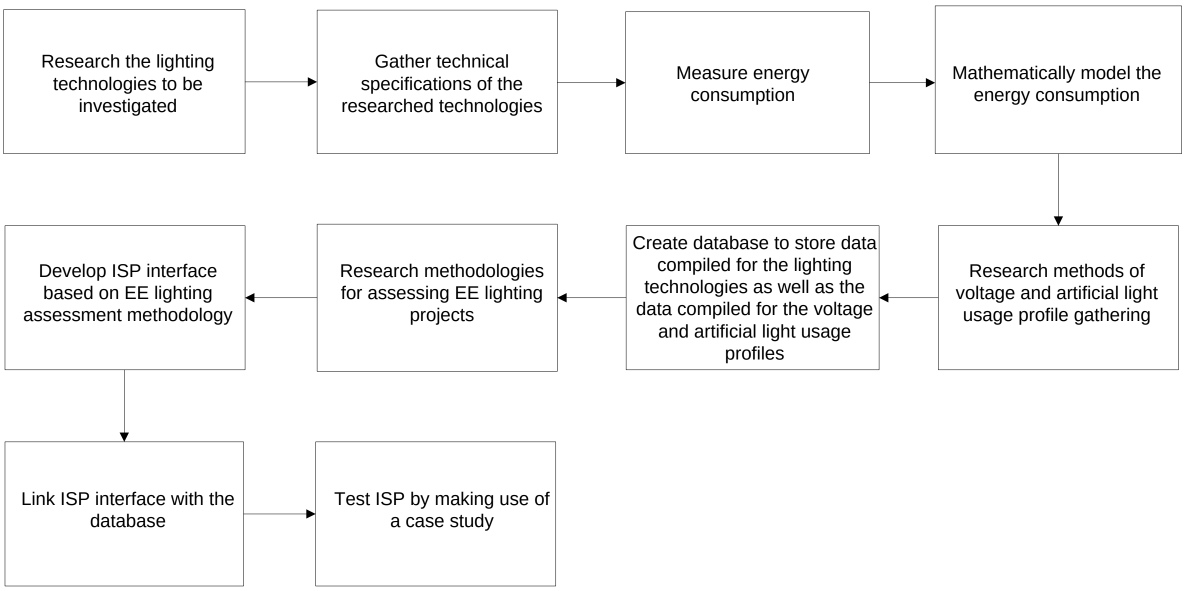

Figure 1: Diagram of the components of this project.

1.4 Thesis structure

This thesis is structured into seven chapters and a number of appendices. The following details apply:

- Chapter 1 presents the project overview.
- Chapter 2 presents a literature review on the main components of this study. The different project stages of DSM interventions as well as the different stages of the M&V of DSM interventions are summarised. Technical details of the the lighting technologies investigated in this study are presented.
- Chapter 3 presents the results of measurements for the various lighting technologies. The active and reactive power consumption as well as the voltage and current waveforms are analyzed. Power consumption models are proposed and are compared to measured results. An analysis of zero sequence currents and harmonic distortion is presented.
- Chapter 4 summarises the methods for gathering voltage profiles and artificial-light usage profiles. The viability of using the "Hobo U9-002 Light on/off" data logger is investigated.
- Chapter 5 summarises the design of the LPST. The software packages used to create the LPST as well as the software structures of the LPST are presented. The software implementation of the Measurement and Verification methodology for assessing EE lighting projects is presented.
- Chapter 6 presents the results of a case study implemented with the LPST. The results obtained by using the LPST are compared with results contained in official Measurement and Verification documentation.
- Chapter 7 summarises the results of the study, presents conclusions and gives recommendations for further work.

2. Literature Review

2.1 Lighting technologies

2.1.1 Introduction

This section of the literature study reviews the lighting technologies that feature prominently in most EE lighting retrofit DSM interventions. These include Incandescent Lamps (ILs), Compact Fluorescent Lamps (CFLs), Tubular Fluorescent Lamps (TFLs) and High Intensity Discharge Lamps (HIDLs).

2.1.2 Incandescent lamps

An Incandescent Lamp (IL) consists of a filament positioned in a glass bulb which contains a gas filling such as argon or nitrogen as is shown in Figure 2. An electric current passes through the filament which causes the filament to heat up and release thermally equilibrated photons (light) [2]. Although an incandescent lamp represents a purely resistive load, the filament has some of the characteristics of a thermistor, i.e. the value of its resistance varies with a variation in temperature [3].

The incandescent lamp is a commonly used lighting technology in residential households, and therefore comprehensive energy consumption data for this lighting technology is important for the M&V of EE lighting projects in the residential load sector.

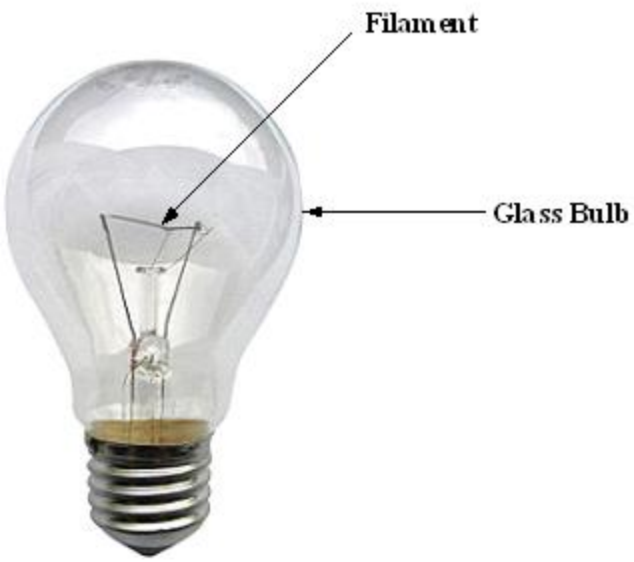

Figure 2: A typical incandescent light bulb.

2.1.3 Compact fluorescent lamps

Figure 3 shows the components of a typical CFL, which consists of a fluorescent tube that is driven by an electronic control circuit (electronic ballast). As a fluorescent lamp is a gas discharge lamp, electricity is used to excite mercury vapour in either argon or neon gas. The result of this reaction is plasma that radiates ultraviolet light. This ultra violet light causes phosphors deposited on the glass walls to fluoresce, thereby producing fluorescent light [4].

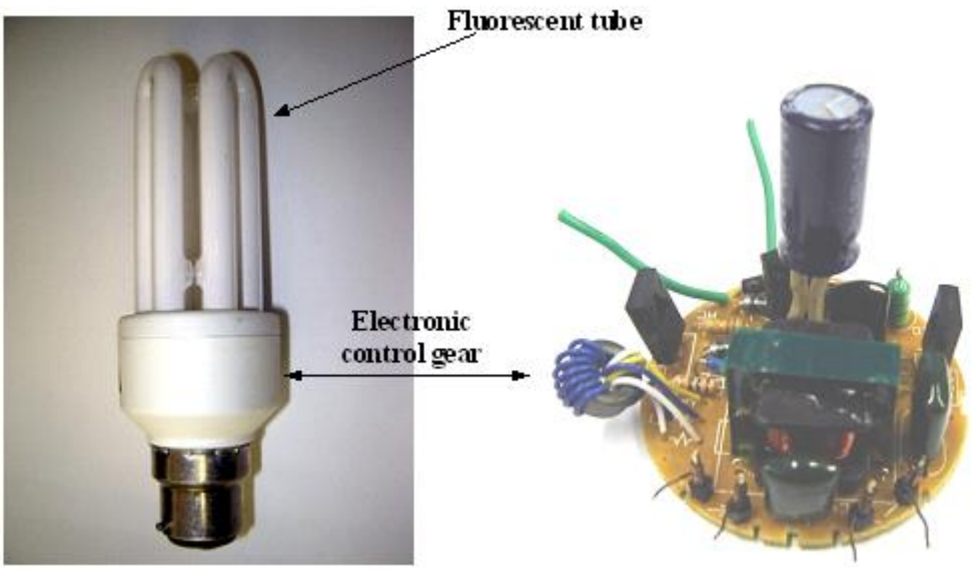

Figure 3: A typical compact fluorescent lamp.

The electronic control circuit regulates the voltage and current supply to the lamp. Figure 4 shows the electronic circuit of a LUXAR 11W CFL. This circuit can be used as an example to explain the operation of a typical CFL:

- *Rectifier:* The supply to the circuit is bridge rectified and has a filtering capacitor C4 to smooth the ripple voltage. F1 is a fuse and inductor L2 is an interference suppressor that also improves the process. D1, C2, R6 and the diac functions during the starting phase. D2, D3, R1, R3 functions as part of protection circuit [5].
- *Start Phase:* Capacitor C2 is charged through resistor R6. When it reaches a certain voltage the diac breaks down and the transistor Q2 is switched on. When Q2 conducts, diode D1 prevents C2 from charging. C2 then discharges and the diac closes. Transistors Q1 and Q2 are now excited by transformer TR1. The ignition capacitor, C3, has a high voltage across it as a result of the resonant circuit made up of components L1, TR1, C3 and C6. The tubes ignite with this resonant frequency of which the magnitude is determined by C3 [5].

- *Normal operation*: After the start phase, the ionised gas presents a low impedance path and capacitor C3 now has negligible influence. The resonant frequency now decreases along with the voltage across the tubes. However this lowered voltage and frequency is still sufficient to keep the lamp burning [5].

A CFL is able to fit into a standard light socket, thus making it an ideal EE replacement for a standard incandescent lamp.

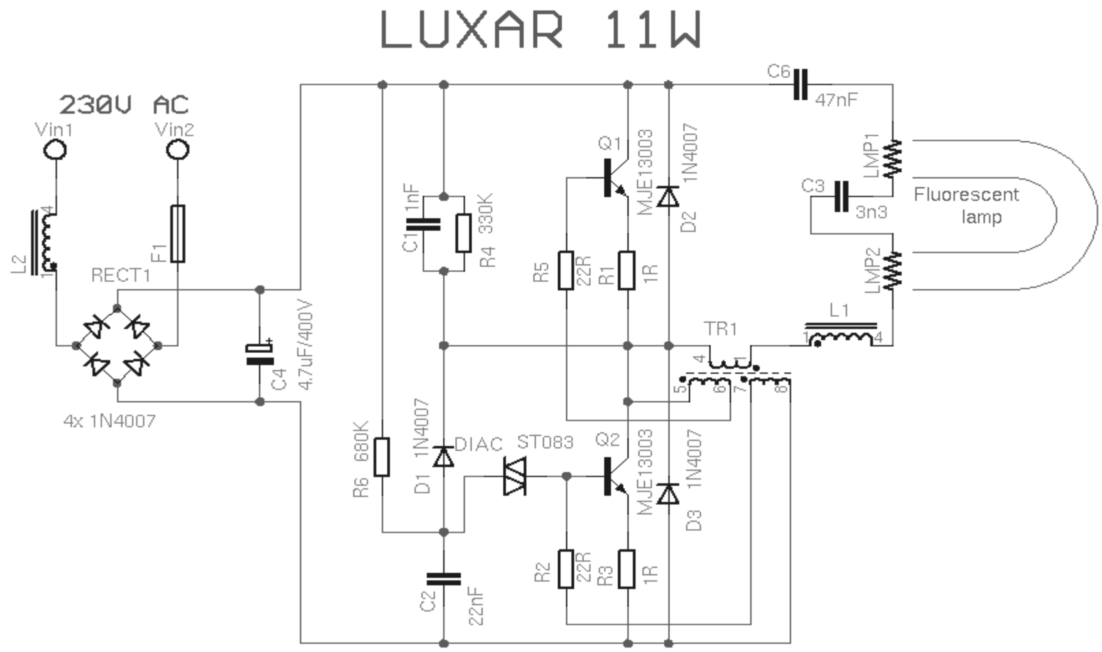

Figure 4: Electronic circuit of a LUXAR 11W CFL [5].

2.1.4 Tubular fluorescent lamps

Tubular Fluorescent Lamps (TFLs) are often referred to as fluorescent lamps. A TFL is of a long tubular form and has its control circuitry (ballast) separately fixed onto the housing (light fixture). The fluorescent tube can be regulated by a magnetic ballast or an electronic ballast [4].

Figure 5: A typical tubular fluorescent lamp and ballast fitted in its light fixture.

2.1.4.1 Magnetic ballast

Figure 6 shows a typical circuit for a TFL fitted with a magnetic ballast. The term "ballast" is given to the inductor in the circuit. With the bi-metallic switch in the closed position, current flows through the heater element. When the bi-metallic switch opens a high voltage is induced by the inductor due to the interruption in current flow. This high voltage causes the lamp to strike and light up. Once the lamp is burning the inductor controls the current flow in the lamp. As a result of the highly inductive load, the power factor is very low. A power factor correction capacitor is used to improvethe power factor. The starter circuit is only used with lamps that require a high starting voltage. In some cases a line voltage of 230V is sufficient, and thus a starter is not required [6].

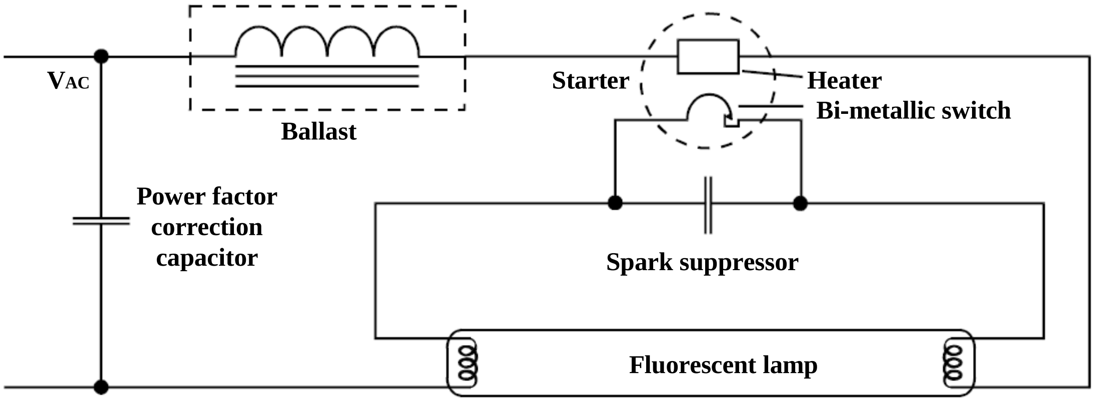

Figure 6: Diagram of a fluorescent lamp with a magnetic ballast [6].

2.1.4.2 Electronic ballast

Figure 7 shows a typical circuit diagram for a TFL with an electronic ballast. The term "ballast" refers to the entire electronic circuit driving the fluorescent lamps. An electronic ballast operates in much the same way as the electronic control circuit of a CFL (see section 2.1.3). The line voltage is rectified to produce a dc voltage, which drives a High Frequency Oscillator (HFO). The HFO drives the transistors, which drives the transformer. The transformer ensures that the correct voltages are applied during the start-up and steady-state phases [6].

TFLs are a common replacement for HID lamps in EE lighting projects.

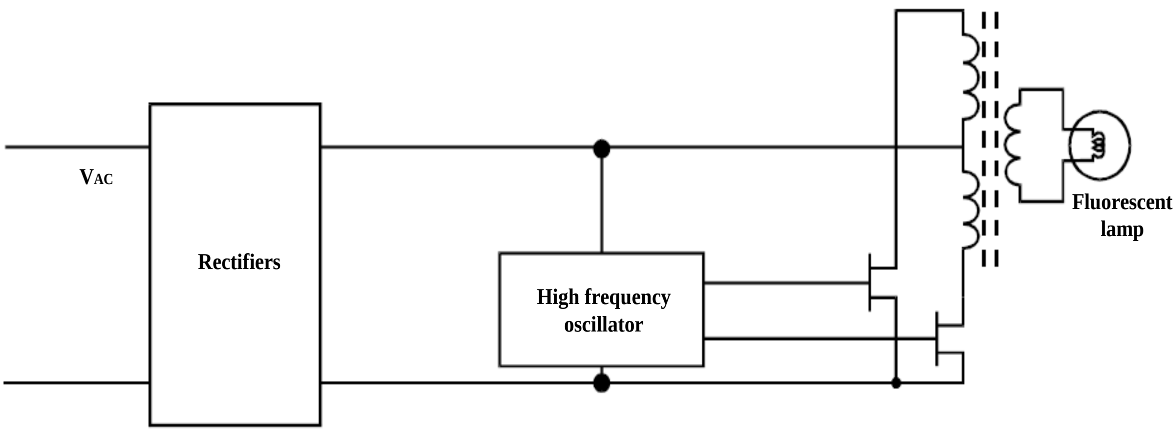

Figure 7: Diagram of a fluorescent lamp with an electronic ballast [6].

2.1.5 High intensity discharge lamps

The following lamp types are High Intensity Discharge Lamps (HIDLs):

- Mercury vapour.

- Metal halide (HQI).
- High pressure sodium and low pressure sodium.
- Xenon short arc.

An arc is struck across tungsten electrodes housed inside an inner fused quartz or alumina tube. The gas inside the lamp assists in getting the lamp started. When the metals are heated to the point of evaporation, light is produced, forming plasma in the process. HIDLs commonly use a magnetic ballast (see section 2.1.4.1) to regulate its current flow [7].

HID lamps are commonly used in the industrial sector, making it a relevant lighting technology to be researched.

HID lamp Magnetic Ballast

Figure 8: HID lamp and ballast.

2.2 Demand-side management

2.2.1 Introduction

Demand-side management (DSM) projects are put into action to attain energy savings. In order to determine the success of a DSM project, the energy savings needs to be quantified to an acceptable level of accuracy. This procedure is called Measurement and Verification (M&V). The M&V procedure is to be unbiased, credible as well as transparent in assessing the impacts of DSM projects.

DSM projects have numerous stakeholders, such as the energy services utility, the Client, the Energy Services Company (ESCO), as well as the project financier. The Client's aim is to lower their energy costs by reducing their energy consumption, while the financier would like to protect their investment in the project and the ESCO has a share in the energy cost saving. The need for M&V arises from this situation.

The main interest for all stakeholders is how much energy is being saved and are the savings being sustained. Due to the stakeholders' financial interests in the projects, it is undesirable to assign the assessment of the savings to one of them, thus an independent, impartial M&V body is needed M&V is thus responsible for facilitating agreement between all stakeholders, with regard to the project outcomes.

The following is needed to determine DSM project savings [[8], [9], [10]]:

- Accurate measurements.
- A reproducible methodology.
- A dependable and consistent process.

To reduce long-term electricity demand ESKOM started a national DSM initiative in the three key load sectors i.e. industrial, commercial and residential. The importance on M&V for this initiative is based on factors such as the following [[8], [9], [10]]:

- Large financial investments.
- Increased number of agreements created between stakeholders.
- Client awareness of the impact of energy-efficiency on their business.

M&V has a number of advantages in the sense that it adds value for the stakeholders. If the impact of a DSM initiative is known, the performance and advancement of that DSM initiative can be traced and assessed, which could aid in finding areas for DSM to concentrate on as well as exposing potential risks. M&V enables the utility company to compare the savings to their targets. M&V provides the following benefits for DSM initiatives [[8], [9], [10]]:

- Impartially quantifies and assess project savings.
- Encourages investment in DSM.
- Reduces risk for financial investors.
- Provides a level of confidence in the ESCO's efforts.
- Provides feedback to all stakeholders.
- Encourages better design and management of DSM projects.

- Provides credibility.

The international measurement and verification protocols form the basis of the understanding of M&V and its requirements. These protocols have been used for years on international level, and along with some adjustments for the South African situation, have served as a valuable source of information with regard to M&V. With the experience gained from the different types of DSM projects, the M&V process has become more structured. Considerable and valuable work has been done by South African M&V teams to develop project-specific M&V methodologies. Basically the process of M&V involves measuring the energy consumption and demand before the project implementation and comparing it to the energy consumption and demand after the project implementation [[8], [9], [10]].

2.2.2 DSM project stages

2.2.2.1 Introduction

Figure 9 illustrates the different stages related to DSM energy-efficient initiatives.

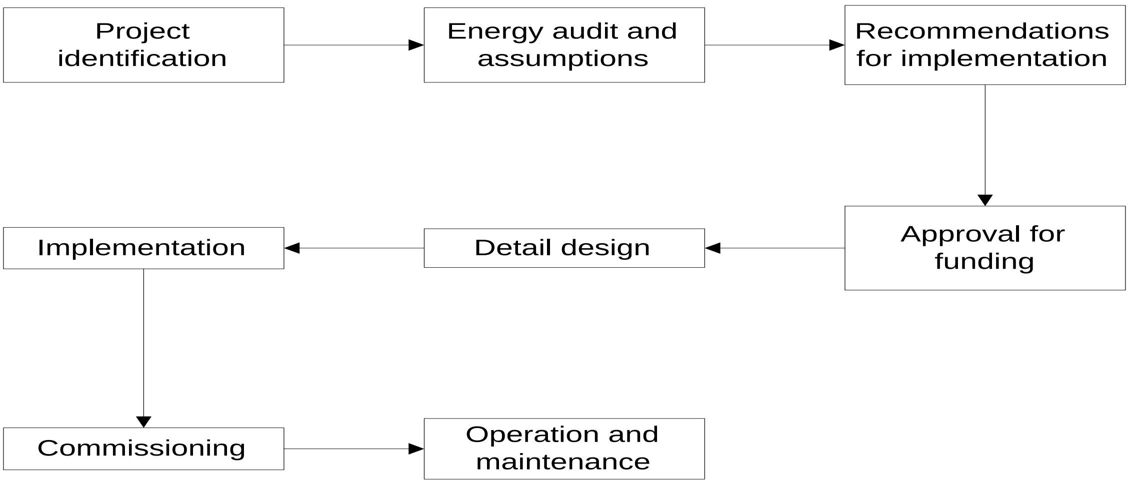

Figure 9: DSM project stages [[8], [9], [10]].

2.2.2.2 Project identification

During this stage, the Client or the ESCO identifies a potential opportunity for implementing an energy saving initiative. In certain cases an ESCO is solicited to ascertain the possible savings attainable as part of the assessment of the feasibilty of a project. The Client provides the ESCO with a letter of intent and this accompanies an application for DSM funding [[8], [9], [10]].

2.2.2.3 Energy audit and assumptions

An energy audit is performed on the applicable energy consuming systems. The potential savings that can be attained by DSM activities are determined using the aforementioned information. A detailed audit is commonly preceded by a preliminary walk-through audit. All assumptions with regard to the system information are stated in the process. Factors that impact on generating the savings are identified [[8], [9], [10]].

2.2.2.4 Recommendations for implementation

As soon as the system information has been obtained, it is possible to make a better estimate of potential savings. DSM activities with the best potential are selected once an evaluation of the various DSM activities along with a feasibility study is done. These recommendations are then submitted to the Client by the ESCO. The viability of the project is assessed by the Client and a decision on whether to proceed is made. Once the Client’s approval for the project is attained, the proposal can be submitted to the utility [[8], [9] [10]].

2.2.2.5 Approval for funding

Once it has been determined that the proposed DSM initiative will produce acceptable results within a suitable budget, timeframe and risk level, the utility will grant funding for the DSM initiative. During this stage the utility will inform the M&V team that it has granted approval for the project and that M&V activities are to be commenced [[8], [9], [10]].

2.2.2.6 Detail design

After the project’s funding is approved, the ESCO makes a comprehensive design of the suggested DSM activities [[8], [9]].

2.2.2.7 Implementation

The DSM activities are implemented [[8], [9]].

2.2.2.8 Commissioning

Commissioning of the equipment and systems installed as part of the intervention is usually done by the ESCO or the contractors utilized by the ESCO. The Client then receives a commissioning report. During this stage, the utility and M&V team is informed and a completion certificate is issued by the utility. This is when the performance assessment stage of the M&V process starts [[8], [9], [10]].

2.2.2.9 Operation and maintenance

In order to ensure that the DSM intervention continues to produce the same level of performance as during commissioning, the implemented DSM measures need to be maintained. Depending on the contractual agreement between the two parties, either the ESCO or the Client carries the responsibility for the operation and maintenance of the system. It is crucial that such an agreement exists because the ESCO could be held liable if the project does not perform to standard for the first three month after implementation. Thereafter, if the project underperforms, the Client could be held liable [[8], [9], [10]].

2.2.3 Measurement and verification project stages

2.2.3.1 Introduction

This section reviews the M&V stages associated with energy-efficient DSM projects. An M&V project has to deliver the following outputs:

- Scoping report.
- M&V plan.
- M&V baseline report.
- Post-implementation M&V report.
- Performance assessment reports.
- Monthly and annual saving reports.

These outputs are structured in such a manner as to supply all the stakeholders with a good understanding of the procedures by which the M&V process will be conducted [[8], [9], [10]].

2.2.3.2 Scoping study

The first stage in an M&V project is the scoping study. This commences after the M&V team is instructed by the utility to go ahead with M&V activities. The scoping study allows the M&V team to gain a comprehensive understanding of what the DSM project will entail. This is done by gathering all the relevant data of the project. A scoping study generally starts with a meeting between the Client, ESCO and M&V

team. A site visit is also conducted during this stage or the following stage, depending on circumstances [[8], [9], [10]].

The scoping study yields a scoping report which contains the following information [[8], [9], [10]]:

- *Project information:* Contains the contact details of the relevant parties and their representatives, e.g. the M&V team, ESCO and Client.
- *Project objective:* This states the technical nature of the intervention and the project impacts that are to be quantified and verified by the M&V team.
- *Site description:* Provides information on the system being examined, along with, information on annual energy consumption, maximum demand as well as an electricity account and the system control and layout are also illustrated.
- *Tariff structure:* Detail description of the tariff structure under which the system operates.
- *Audit of system:* Supplies in depth information of the system affected by the proposed DSM project and includes a layout of the system's electrical supply in order to assist M&V with possible measurements.
- *Proposed activities by the ESCO:* Description of the ESCO's proposed activities as is provided by the ESCO and Client.
- *Expected results:* The M&V team is provided with an estimation of the anticipated impacts on the system. This information is provided for monthly maximum demand, energy consumption and electricity cost impacts. In projects where the process proposed by the ESCO is replicable, an estimation of the anticipated impacts is done by the M&V team.
- *Conclusions and comments:* Summary of anticipated results and comments by the M&V team. No recommendations are to be made by the M&V team. The scoping report is useful in identifying and clearing up any misunderstandings or discrepancies that may exist between the ESCO, Client and Utility, with regard to the proposed DSM activities.

2.2.3.3 M&V plan

The M&V plan forms the basis of the entire M&V process. It sketches the complete M&V procedure proposed for the project. The first section of the M&V plan contains some sections of the scoping report in order to realize the M&V plan as a singular entity that provides a comprehensive overview of the project [[8], [9], [10]]. The M&V plan contains the following information [[8], [9], [10]]:

- *Project information:* Contains the contact details of the relevant parties and their representatives, e.g. the M&V team, ESCO and Client.
- *Project objective:* This states the technical nature of the intervention and the project impacts that are to be quantified and verified by the M&V team.

- *Site description:* Provides information on the system being examined, along with, information on annual energy consumption, maximum demand as well as an electricity account and the system control and layout are also illustrated.
- *Tariff structure:* Detail description of the tariff structure under which the system operates.
- *Audit of system:* Supplies in depth information of the system affected by the proposed DSM project and includes a layout of the system's electrical supply in order to assist M&V with possible measurements.
- *Proposed activities by the ESCO:* Description of the ESCO's proposed activities as is provided by the ESCO and Client.
- *Expected results:* The M&V team is provided with an estimation of the anticipated impacts on the system. This information is provided for monthly maximum demand, energy consumption and electricity cost impacts. In projects where the process proposed by the ESCO is replicable, an estimation of the anticipated impacts is done by the M&V team.
- *Evaluation:* The anticipated impacts are evaluated by the M&V team, where comments and concerns are raised on the assumptions made and calculation methodology used.
- *M&V Option selection:* The following four main M&V options are utilized to determine a project's baseline:
    - *Option A:* Partially Measured Retrofit Isolation

      This entails isolating the energy use of the components related to the DSM activity, from the energy use of the rest of the facility. During the pre-implementation and post-implementation periods, all the relevant energy usage is isolated by means of the measurement equipment. Partial measurements are utilized with this option, where certain parameters are specified as opposed to being measured. These stipulations are only made if it is proven that the overall effect of all possible errors resulting from the stipulations does not considerably affect the total savings.
    - *Option B:* Retrofit Isolation

      Option B and Option A are identical, but for the fact the Option B does not allow for any stipulations. Complete measurements are thus mandatory. This includes short term or continuous metering. Continuous metering provides for better accuracy in reported savings and also provides more data on equipment operation.
    - *Option C:* Whole Building

      This entails the utilization of utility or building sub meters to assess the energy performance of a whole building. This option ascertains the combined savings of DSM activities applied to the facility that is monitored by the energy meter. It does not assess individual DSM activities, if more than one is applied. As a result of whole building meters being utilised, the savings ascertained include changes made to the facility that are not a part of DSM activities. This option is best suited for projects where more than one DSM activity is implemented and those activities have a significant level of interaction. It is also suited to projects where the isolation of individual DSM activities is not possible or too costly.

- *Option D:* Calibrated Simulation

  This entails utilizing computer simulation software to calculate the energy usage of a facility. The simulation is adjusted in such a manner as to produce energy usage and demand data that has an acceptable level of accuracy relative to actual data from the baseyear or post-implementation year. Much like Option C this option also allows for assessing the performance of multiple DSM activities at a facility. Unlike with Option C, multiple runs of the simulation package allows for assessing the individual activities on their own as well.

- *Boundaries:* The boundaries of the savings impact determination, is stated. It also states whether or not the interactive systems effects will be included in determining the savings.
- *Baseline characterisation*: The method by which the baseline is determined is supplied in this section. Baseline variables are stated along with a comprehensive description which states amongst others whether or not baslines are developed for separate sub-systems or one complete system.
- *Baseline adjustments:* All foreseeable circumstances that can lead to the baseline being adjusted are described.
- *Pre-implementation metering plan:* Supplies a comprehensive layout and a detailed description of the metering system to be used, including data requirements, variables to be measured, measurement points, equipment to be used, measurement intervals and the duration of metering activities
- *Post-implementation metering plan:* Supplies similar information as the pre-implementation metering plan, but adjusted to the post-implementation circumstances.
- *Savings calculation methodology:* All equations related to the methodology utilised to ascertain the savings stated. The environmental impacts methodology and calculations as well as emission factors are also stated.
- *Project cost:* Supplies a cost breakdown for each M&V activity along with their expected date of submission. This is of interest to the utility only.
- *Project schedule:* A comprehensive itemisation of all relevant M&V activities associated with the M&V deliverables is included within an M&V activity schedule. This includes significant project timelines like implementation dates and project completion dates for the project. The DSM project implementation schedule is determined by the ESCO and Client. This schedule and the M&V schedule are linked, thus enough time must be allowed in the implementation schedule for M&V activities, such as baseline measurements which requires at the very least a three-month period.

Upon submission of the M&V plan to the ESCO and Client, they review the plan and make recommendations on the content. Once all parties are in agreement with regard to the M&V plan, the M&V process may proceed. If all parties are not satisfied, the M&V plan is revised and re-submitted.

2.2.3.4 Baseline

Pre-implementation measurements are used to develop the baseline. In order to create confidence in the M&V baseline, the pre-implementation measurements need to be recorded over an adequate length of time, preferable at least three months. The three most recent months before the project implementation would be ideal. The actual baseline model that is used to determine the savings must be recorded in the M&V baseline report. In order to ensure that the method by which the baseline is determined is repeatable, all relevant information must be included in this report [[8], [9], [10]]. The baseline report contains the following information [[8], [9], [10]]:

- Project information, project objectives and a site description.
- Variables used to develop the baseline model.
- Pre-implementation metering data as well as metering period and interval information.
- Data used to create the baseline.
- Modelling procedures.
- Assumptions made during the modelling of the baseline.
- Procedures for adjusting the baseline.
- All the baseline data relevant to determining the project's savings, such as actual demand and energy consumption.

Upon submission of the M&V baseline report to the parties concerned, they review the baseline and comment on the content in terms of changes to be made. Once all the parties are in agreement with regard to the M&V baseline report, the M&V process may proceed. If all parties are not satisfied, the M&V baseline report is revised and re-submitted. Once all parties have agreed on the contents of the M&V baseline report the final M&V baseline report is issued. This is the last stage in the M&V process before implementation.

2.2.3.5 Post-implementation

This stage follows commissioning of the equipment and systems once implementation is completed. This forms an integral part in verifying whether the project is implemented as specified. The post-implementation stage generally involves a physical audit conducted on site. Post-implementation measurements may be taken during this stage. The M&V post-implementation report contains the following information [[8], [9], [10]]:

- Project information, project objectives and a site description
- *Original system description:* Describes the initial system, as operational during the pre-implementation stage. This description corresponds with that contained in the M&V plan.
- *Proposed changes:* Describes the ESCO's proposed DSM intervention.
- *Actual changes:* Describes the alterations to the system, ascertained through a post-implementation audit, as a result of the DSM intervention.
- *Deviation:* Describes the differences between the DSM intervention which is described in the M&V plan and the actual implemented DSM intervention as ascertained by the post-implementation audit and supplies reasons for the differences obtained in discussions with the ESCO and/or Client
- *Comments:* Comment on deviations and state the potential influences of the deviations on the project impacts.

2.2.3.6 Performance assessment

This stage entails assessing the project's performance over a three month period and involves monthly performance assessment reports that are submitted to the stakeholders. The aim is to allow the ESCO the opportunity to make alterations to the intervention in order to make sure that the proposed savings are achieved. Should the DSM intervention under-perform in terms of the proposed savings, then as contractually stated and agreed upon, the ESCO will be held liable which may lead to penalties that have to be paid to the utility. The M&V performance assessment report contains the following information [[8], [9], [10]]:

- Project information, such as the site name, details of the M&V team member responsible for the report, the starting date of the project's implementation and the period over which the savings are assessed.
- The project impacts over the relevant period with regard to the baseline, actual, savings, electricity cost and environmental impacts.
- The average impact on the demand for the relevant time-of-use periods with regard to the baseline, actual and savings.

  The relevant time-of-use periods are as follows:

  - Weekday morning peak.
  - Weekday standard.
  - Weekday afternoon peak.
  - Weekday off-peak.
  - Saturday standard.

- Saturday off-peak.
- Sunday off-peak.

Average weekday, Saturday and Sunday baseline and actual energy use profiles are included in this report. Comments, made by the M&V team, on the project's performance are included in the report. If the system could not perform due to uncontrollable factors, such as a power failure, that period is considered as a condonable period, and is omitted from performance assessment calculations. The onus is on the Client or ESCO to validate the reasons for these condonable days. In essence, the performance assessment is done to establish whether or not the system performs as proposed with regard to the DSM target. A performance certificate is issued by the M&V team at the end of the performance assessment stage. The certificate contains a summary of the project's assessment during the performance assessment period [[8], [9], [10]].

2.2.3.7 Monthly savings report

Post-implementation measurements are used, in conjunction with the baseline, to determine the savings brought about by the DSM intervention. Following the performance assessment period, the savings achieved for each month is compiled into a monthly savings report and issued to all stakeholders. The structure of this report is similar to that of the performance assessment report.

A savings report report consists of two main parts. The first part provides the data for the month which the report is compiled for, whilst the second part provides the data for the total period up until the date of the report. The monthly savings reports are designed to provide insight to the amount of savings being achieved and the future sustainability of those savings. These reports are provided for the duration of the M&V project. Baseline adjustments can also be made during this stage, should circumstances require it. During this phase, the client is typically responsible for the performance of the project [[8], [9], [10]].

2.2.3.8 Annual savings report

An annual savings report is generated from the monthly savings reports and serves as a summary report for that specific year. Along with the monthly savings reports, annual savings reports are provided for as long as the DSM project is in effect. The annual savings report structure is similar to the monthly savings report structure, but provides the total project impacts for a year [[8], [9], [10]].

2.2.4 Energy-efficient lighting projects

A typical Energy-Efficient (EE) lighting project involves one or all of the following activities:

- Energy-inefficient lamps along with their lamp-fittings are replaced by energy-efficient lamps and their lamp-fittings.
- Energy-inefficient control gear is replaced with energy-efficient electronic control gear, whilst the fittings remain intact.
- One type of lighting technology is replaced with another, i.e. incandescent lamps are replaced by CFLs.

The methodology for assessing EE lighting projects typically involves the activities conducted at the site:

- Lighting technology audits, whereby the lighting technologies in use and the size of the lighting load, e.g. numbers of light fittings of different types, are determined.
- Active power measurements to determine the power consumption profiles of the lighting load.
- Measurement or otherwise determining artificial-light usage profiles for the site.

The lighting technology audit typically consists of the following stages:

- Pre-implementation or baseline audit.
    - An audit of the pre-implementation lighting technologies is done.
    - Measurements are taken to verify the power usage of the relevant lighting technologies.
    - Artificial-light usage profiles are obtained.
- Post-implementation audit.
    - An audit of the post-implementation lighting technologies is done.
    - Measurements are taken to verify the power usage of the relevant lighting technologies.

2.3 Structured query language and the Delphi software development platform

2.3.1 Development package

Borland® Delphi is used as the development package for the LPST. It is an easy to use package with a graphical approach to building a GUI [11]. It is also efficient with database interaction. The stand alone deployment of the executable file makes this an attractive and logical choice for creating the LPST, given the specified requirements (see chapter 5.1).

2.3.2 Database package

MySQL is a relational Open Source SQL database management system [12]. Relational databases store data in separate tables, which can be linked by defined relations. This delivers speed and flexibility. Structured Query Language (SQL) is a common standardized language for accessing databases. MySQL is used as the database package for the LPST as it fulfils all the requirements stated in chapter 5.1.

Other database packages such as Interbase and Paradox were considered and although they may have certain advantages over MySQL such as better support and compatibility with Borland® Delphi, ultimately those advantages do not out weigh their cost relative to MySQL.

3. Measurements and Modelling of Lighting Technologies

3.1 Introduction

This chapter presents measured electrical performance data for the four lighting technologies investigated, namely ILs, CFLs, TFLs and HIDLs. The following measurements are presented for each type of lamp:

- RMS Voltage and voltage waveform data.
- RMS Current and current waveform data.
- Active power (average power).
- Reactive power.
- Apparent power.
- Power factor.

Spectral analysis of the voltage and current waveforms has been performed and the following results are presented:

- Voltage and current frequency spectrums.
- Total harmonic distortion of the voltage and current.
- Zero-sequence currents generated by the specific lighting technology.

From these measurements, conclusions are drawn relating to the effects on the Quality of Supply (QOS) of the electrical supply networks, the existence of zero-sequence, neutral currents and the impacts of the voltage dependency of the specific lighting technology in determining the savings impacts of EE lighting retrofit DSM interventions.

3.2 Overview of measurement arrangements and analysis procedures

3.2.1 Test topology and test procedures

Figure 10 shows the topology of the test arrangement used for the laboratory power consumption measurements and the capturing of waveform data. The supply voltage V_{AC} was obtained from the local mains supply network through a variac to control the magnitude of the supply voltage applied to the lighting technology under test.

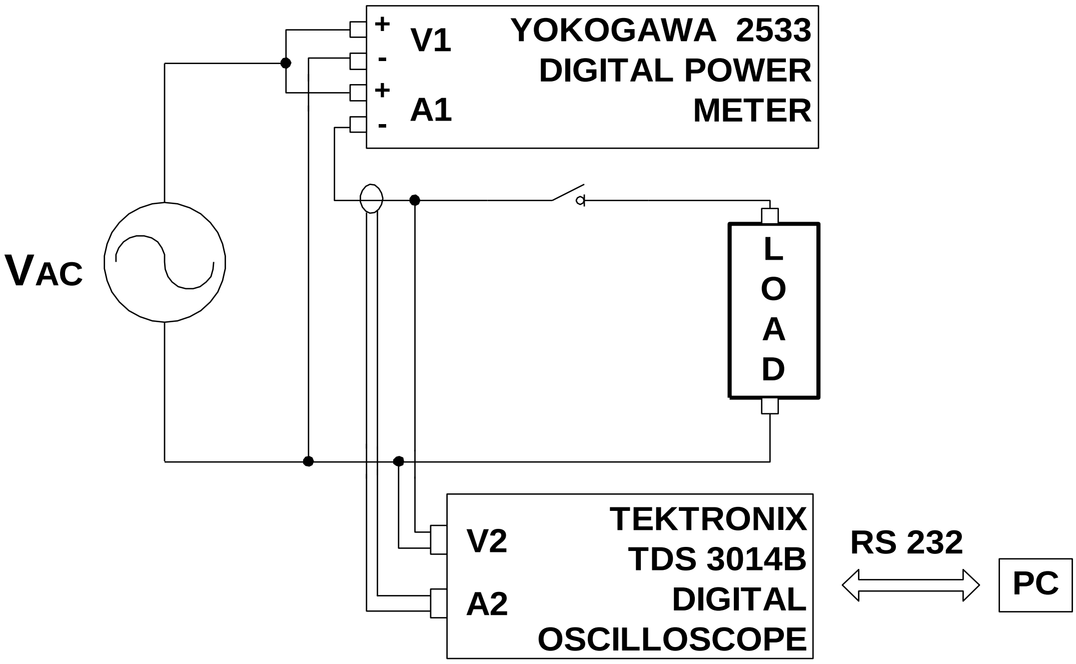

Figure 10: Test arrangement for power consumption measurements and capturing waveform data.

Figure 11 shows the topology of the test arrangement for laboratory neutral current measurements. One of the most important concerns of harmonic current distortion is the fact that the triplet orders, i.e. 3^{rd}, 6^{th}, 9^{th} etc., represent zero sequence harmonic orders. This implies that these current components sum to produce a neutral current in three-phase loads [13]. Measurements were taken in order to illustrate the order of magnitude of the zero sequence harmonic currents.

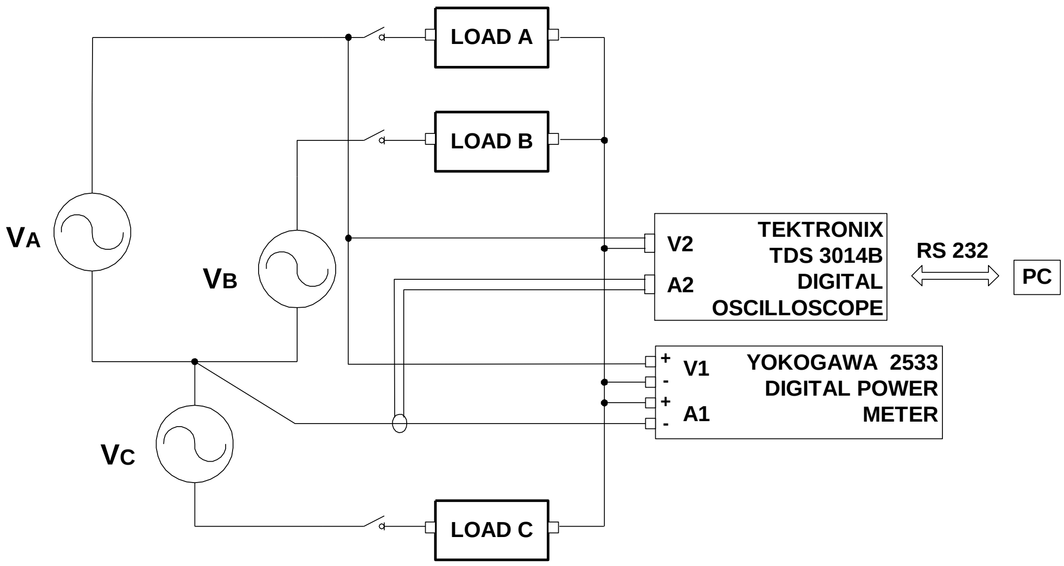

Figure 11: Test arrangement for neutral current measurements

The voltage and current measuring instrumentation used in the investigation can be summarized as follows:

- Voltage measurement V_1 and current measurement A_1 were conducted with a wideband true Root Mean Square (RMS) Yokogawa 2533 Digital Power Meter.
- Voltage measurement V_2 and current measurement A_2 were conducted with a Tektronix TDS3014B digital oscilloscope with a Tektronix P3010 voltage probe and a Tektronix TCP 202 current probe. This instrument was used to record the voltage and current waveforms for subsequent processing in MATLAB.

Table 1 summarizes relevant specifications of the abovementioned measuring equipment. Table 2 summarizes the applicable power calculation formulas used by the Yokogawa 2533 Digital Power Meter.

Table 1: Specifications of the measuring equipment.

Equipment	Max Voltage	MaxCurrent	Bandwidth
Tektronix P3010 voltage probe	300 V_{RMS}	-	DC to 100 MHz
Tektronix TCP202 current probe	300 V_{RMS}	Max DC + Peak AC Current of 15 A.	DC to 50 MHz
Tektronix TDS 3014 B Digital Oscilloscope	300 V_{RMS} with a standard 10x probe	-	DC to 100 MHz
Yokogawa 2533 Digital Power Meter	1000 V peak or 2x maximum range (V_{RMS})	50 A peak or 3x maximum range (I_{RMS})	DC, 10 Hz to 20 kHz

Table 2: Yokogawa 2533 Digital Power Meter power calculation formulas [14].

Calculation	Formula
Average real power (P_{AVG}) [W]	$\frac{1}{T}\int_0^T v(t)\cdot i(t)dt$
Reactive power (Q) [Var]	$\sqrt{(\mathrm{V_{RMS}} \text{ x } \mathrm{I_{RMS}})^2 - P_{AVG}}$
Apparent power (S) [VA]	V_{RMS} x I_{RMS}
Power factor	$\frac{P_{AVG}}{\mathrm{V_{RMS}} \text{ x } \mathrm{I_{RMS}}}$

The power consumption measurement and waveform capturing procedure used in the investigation can be summarized as follows:

- The lighting technology under test is energised with a supply voltage of 230 V and the lamp is allowed to stabilize.
- The voltage is reduced to 207 V (10 % below the nominal supply voltage of 230 V [1]) before gradually being increased in 1 % increments to 253 V (10 % above the nominal supply voltage). The RMS supply voltage, RMS current, active power, reactive power, apparent power and power factor are recorded with the digital power meter and the

voltage and current waveforms are recorded with the digital oscilloscope for each increment.

- MATLAB is used to extract the desired spectral information from the recorded voltage and current waveforms.

The harmonic properties of the supply current should ideally be determined for a sinusoidal supply voltage source with zero internal impedance. For practical reasons, this was not possible and the mains supply voltage waveform, which exhibits a small degree of harmonic distortion, was used. It is therefore important to qualify the results by giving information for the spectral properties of both the supply voltage and the supply current waveforms. The following two types of spectral results are given for the measured voltage and current waveforms:

- Line spectrum graphs that display the amplitudes of the harmonic components versus the harmonic order.
- Total Harmonic Distortion (THD) graphs that display the THD of the waveforms as a function of the RMS supply voltage.

The THD of a waveform is defined as the root of the sum of the square of the harmonic amplitudes divided by the amplitude of the fundamental component of the waveform. This is represented by the relationship

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1} \qquad [3.1]$$

where V_n denotes the amplitude of the nth harmonic, N denotes the highest harmonic order taken into consideration and V_1 denotes the amplitude of the fundamental component [15].

3.2.1.1 Data analysis

3.2.1.1.1 Harmonic spectral analysis

The supply voltage and current waveforms are digitised at a sample rate of 50000 samples per second. The Fast Fourier Transform (FFT) as implemented in MATLAB was used to calculate the frequency spectrum of the transient voltage and current waveforms. The 50000-point FFT yields a frequency resolution of 1 Hz. In the spectral results given below, the amplitudes of the harmonic components spectrum are normalized relative to the amplitude of the 50 Hz fundamental frequency.

In common with typical Low Voltage (LV) supply networks, the supply network exhibited a degree of harmonic voltage distortion [1]. Although this has an impact on the harmonic power flow measured in the arrangement, the effects on the main results, i.e. the supply current harmonic profile, are expected to be small. The harmonic content of the supply voltage is shown in Figure 12.

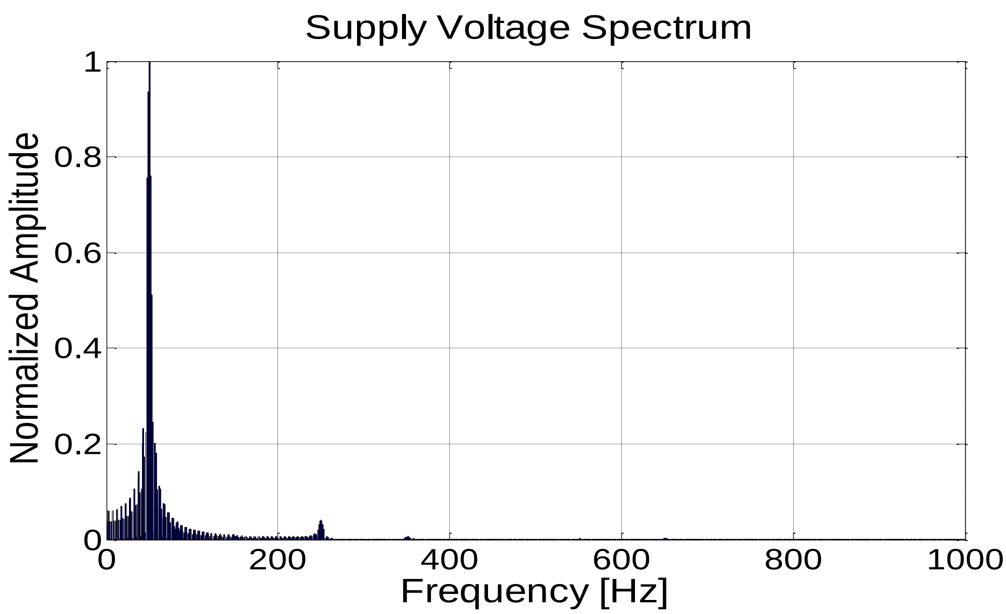

Figure 12: Frequency spectrum of the supply voltage used in the experiments.

Figure 13 shows the THD of the voltage waveform for the varying supply voltage.

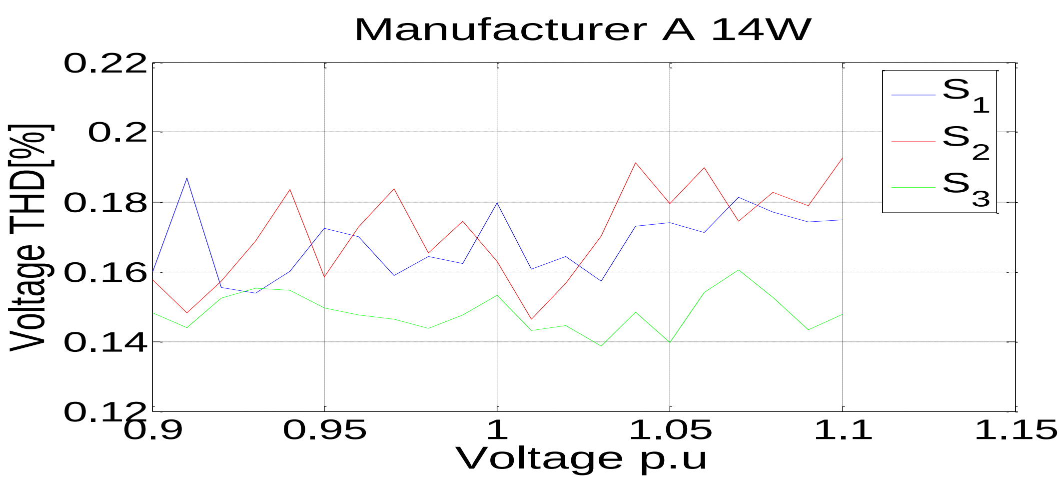

Figure 13: THD of the voltage waveform versus RMS supply voltage for 60 W IL samples.

A simulated summation of the three-phase supply voltage was done in order to determine how balanced the supply voltage is. Figure 14 shows the three-phase supply voltage waveforms and the simulated summation of the three phases.

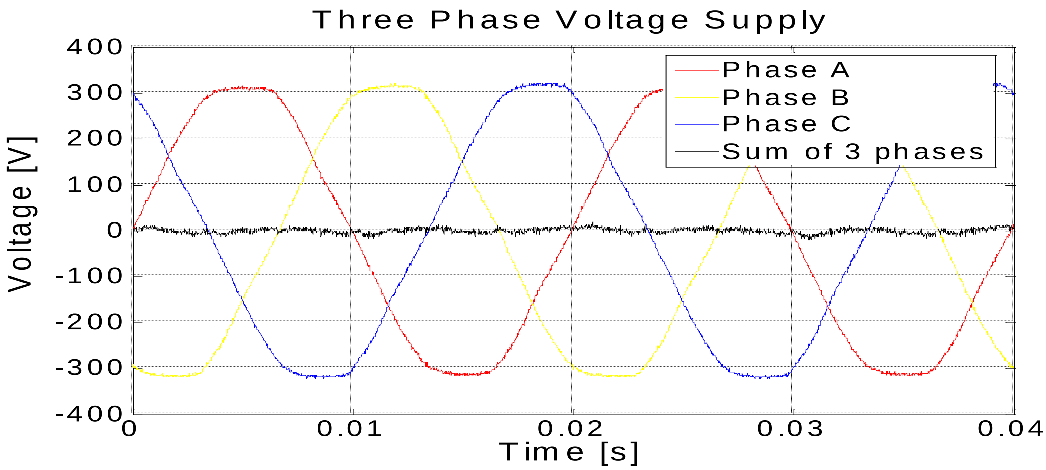

Figure 14: Three-phase supply voltage waveforms.

3.3 Modelling technique

Samples of the lighting technologies from the same manufacturer that have equivalent power ratings exhibit slight differences in the measured results. The following procedure was used to arrive at a representative model for the active power consumption of the lighting technologies versus RMS supply voltage for each manufacturer:

- The measured results for each lighting technology sample from a given manufacturer are modelled using a polynomial curve fitting algorithm.
- The power consumption over the supply voltage range of interest is determined for each sample from the manufacturer.
- The average of the power consumptions of the test samples are obtained and then modelled with another polynomial curve fitting in order to realize an active power versus supply voltage model for the specific lighting technology type for the given manufacturer.

3.4 Results for incandescent lamps

3.4.1 Overview

A variety of commercial ILs of different ratings and from different manufacturers were tested. In order to determine whether the test results are consistent for ILs of the same rating from the same manufacturer, three samples of each rating per manufacturer were tested. Table 3 summarizes the subsection of the test results that are presented in this chapter.

Table 3: Summary of the ILs considered in this chapter.

Manufacturer / Model	Power Rating [W]
A	60
	100
B	60
	100
C	60
	100

3.4.2 Voltage dependency

Appendix A contains all the data relevant to this chapter.

3.4.2.1 Modelling of the voltage dependency of the active power consumption of ILs

Table 4 summarizes the polynomial curve fitting models determined for each of the IL types evaluated.

Table 4: Active power consumption models derived for ILs.

Manufacturer/Model	Power Rating [W]	Active power model [W]
A	60	$0.38288V - 30.145$
	100	$0.61468V - 47.457$
B	60	$0.37385V - 29.785$
	100	$0.61577V - 47.415$
C	60	$0.38575V - 29.504$
	100	$0.631468V - 49.274$

Figure 36 to Figure 41 compare the active power versus RMS supply voltage characteristics of the models (M) to the original measurements obtained for each sample. The correlations of the measurements between the different models are generally good. The results for the samples of the same rating from the same manufacturer vary from almost identical to a spread of approximately 4% as for the 60W units from manufacturer C for example.

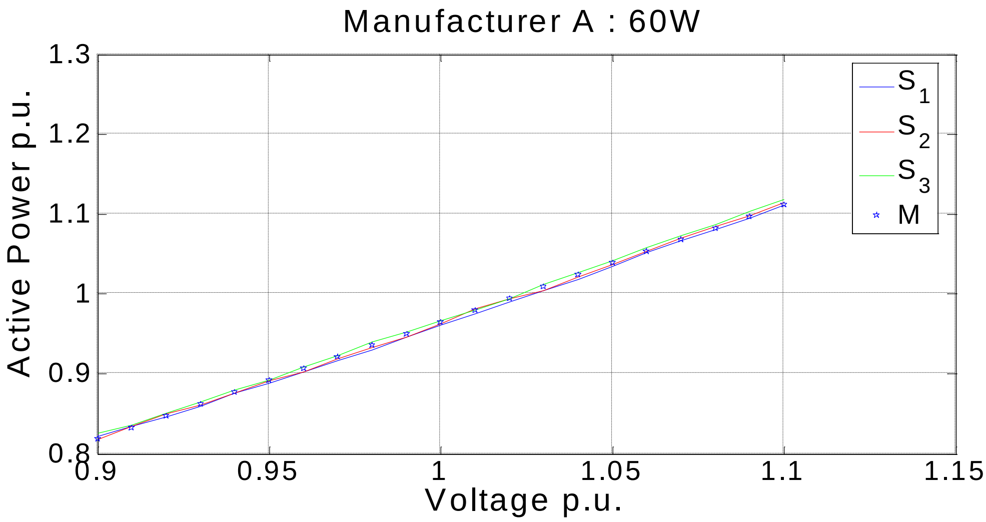

Figure 15: Measured and modelled active power consumption versus RMS supply voltage for the 60 W IL samples from manufacturer A.

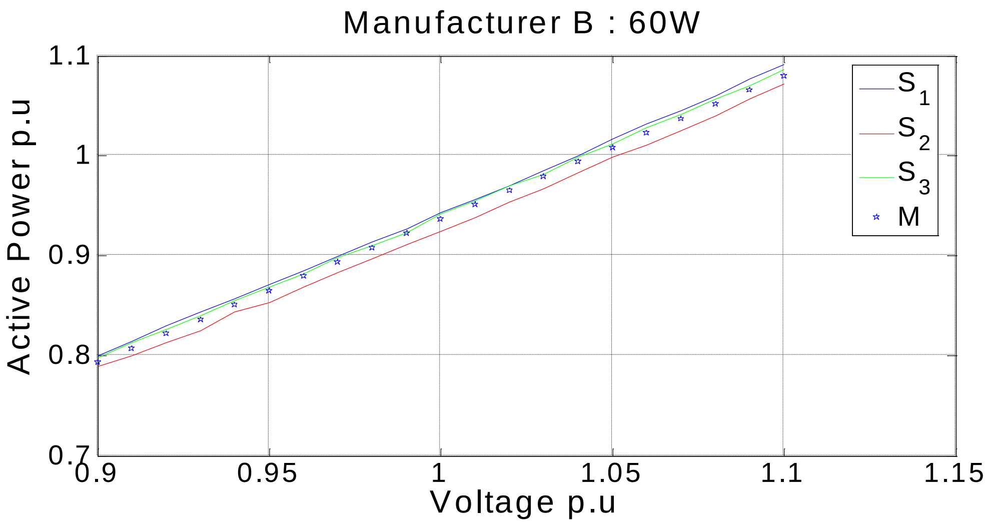

Figure 16: Measured and modelled active power consumption versus RMS supply voltage for the 60 W IL samples from manufacturer B.

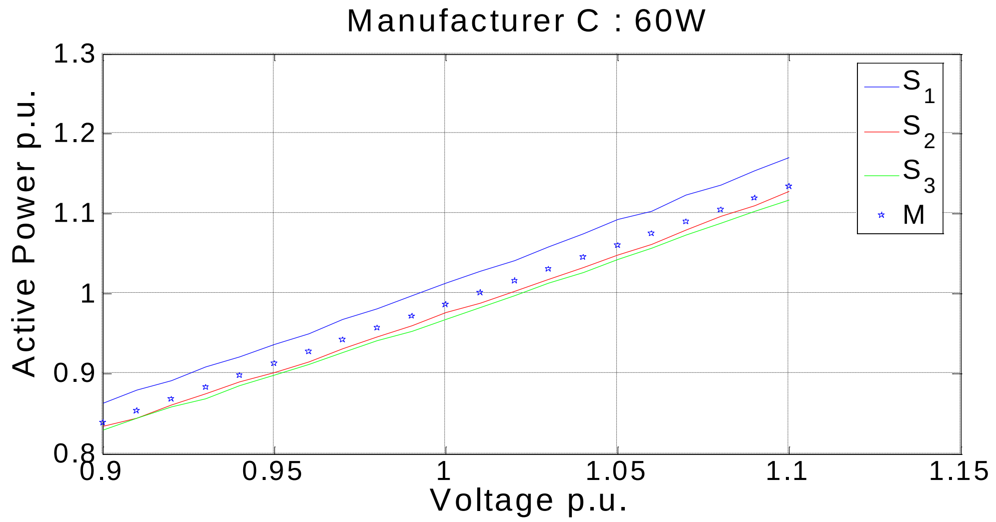

Figure 17: Measured and modelled active power consumption versus RMS supply voltage for the 60 W IL samples from manufacturer C.

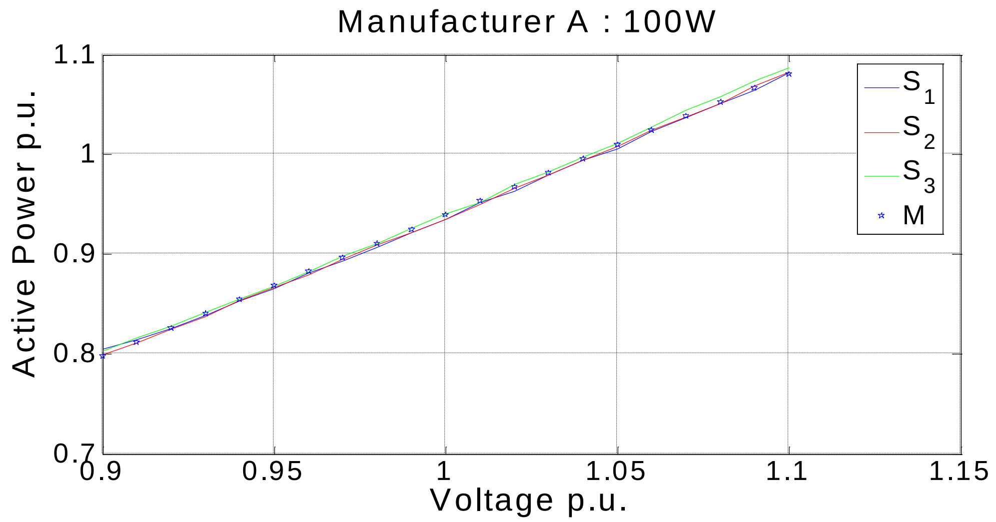

Figure 18: Measured and modelled active power consumption versus RMS supply voltage for the 100 W IL samples from manufacturer A.

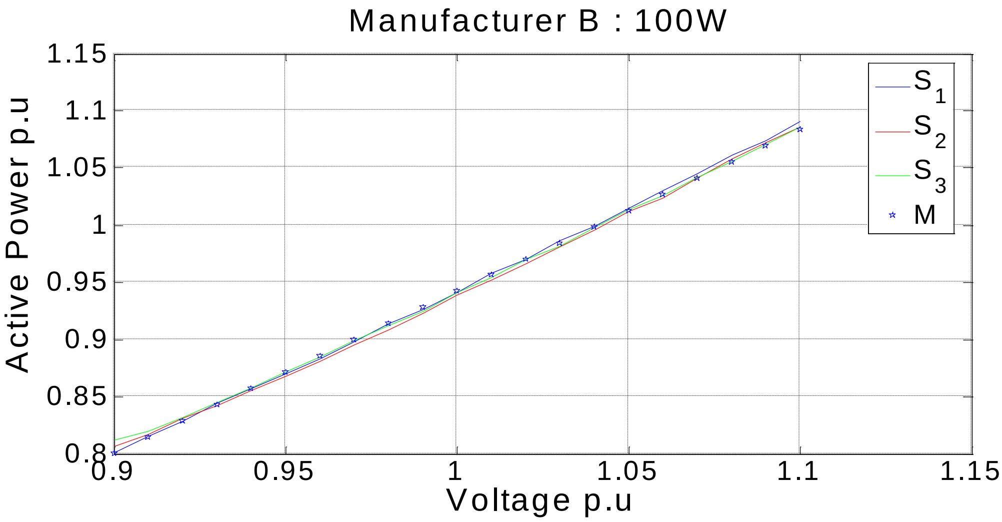

Figure 19: Measured and modelled active power consumption versus RMS supply voltage for the 100 W IL samples from manufacturer B.

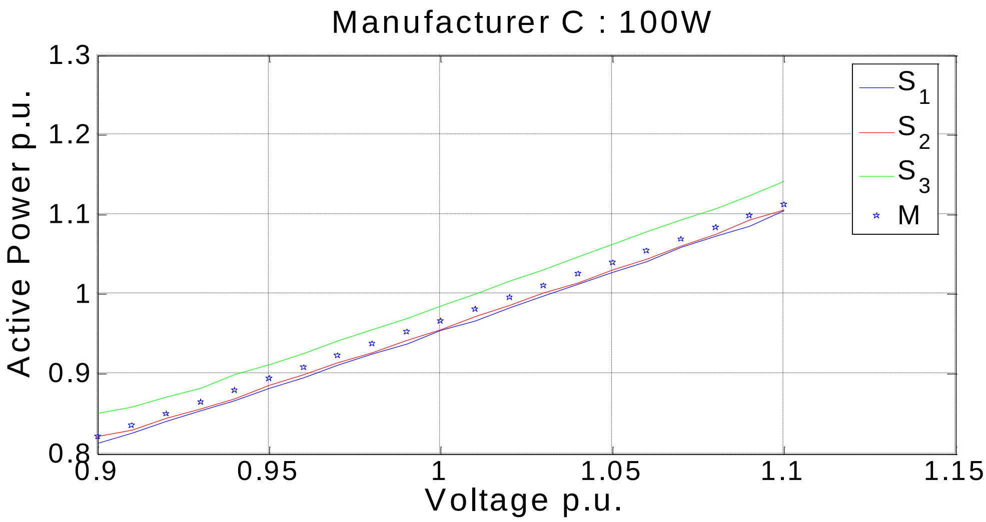

Figure 20: Measured and modelled active power consumption versus RMS supply voltage for the 100 W IL samples from manufacturer C.

3.4.3 Waveform and spectral analysis

3.4.3.1 Supply voltage and current waveforms

Figure 21 shows a typical example of the supply voltage and current waveforms recorded for the IL test samples. The current waveform is slightly distorted but still highly sinusoidal. From this, a very low harmonic presence in the current waveform is expected.

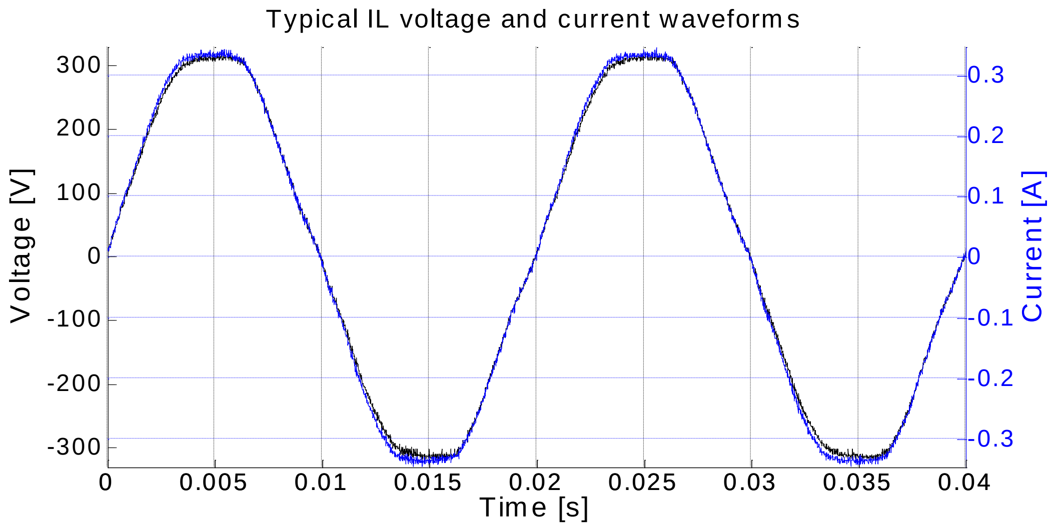

Figure 21: Typical supply voltage and current waveforms for a 60 W IL.

3.4.3.2 Harmonic content of the supply current

Figure 22 to Figure 27 shows the harmonic spectrum of the current waveform for the IL sample 1 from each of the manufacturers considered in the investigation. The current spectrums exhibit a low degree of harmonic distortion. The other samples exhibit similar results.

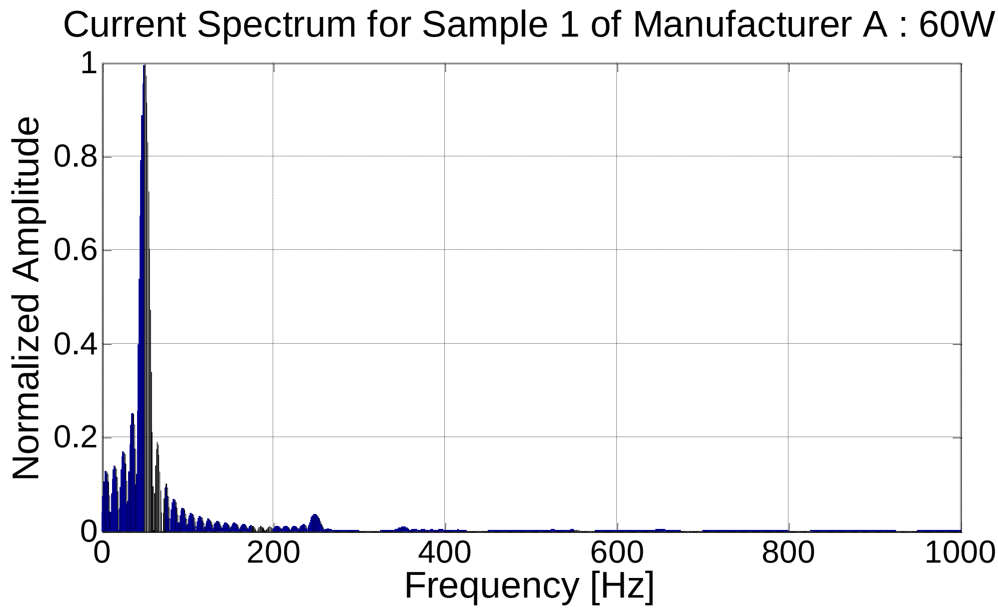

Figure 22: Current spectrum for the first 60 W IL sample from manufacturer A.

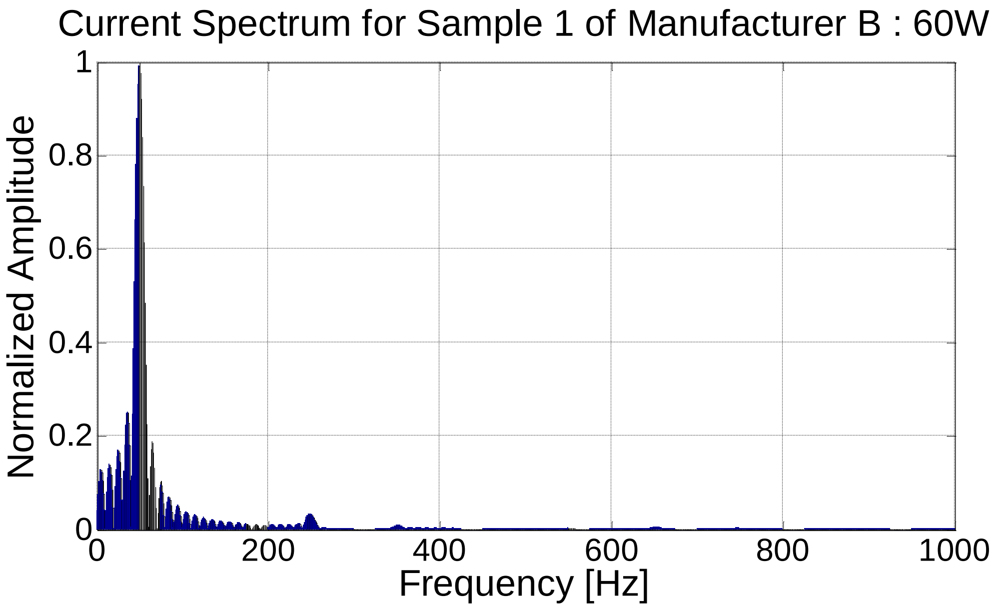

Figure 23: Current spectrum for the first 60 W IL sample from manufacturer B.

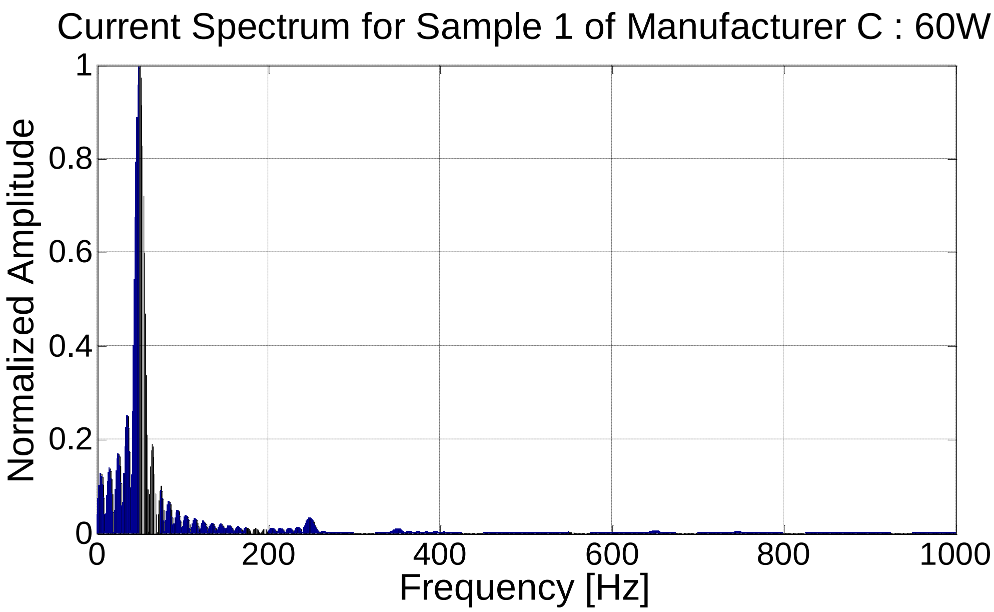

Figure 24: Current spectrum for the first 60 W IL sample from manufacturer C.

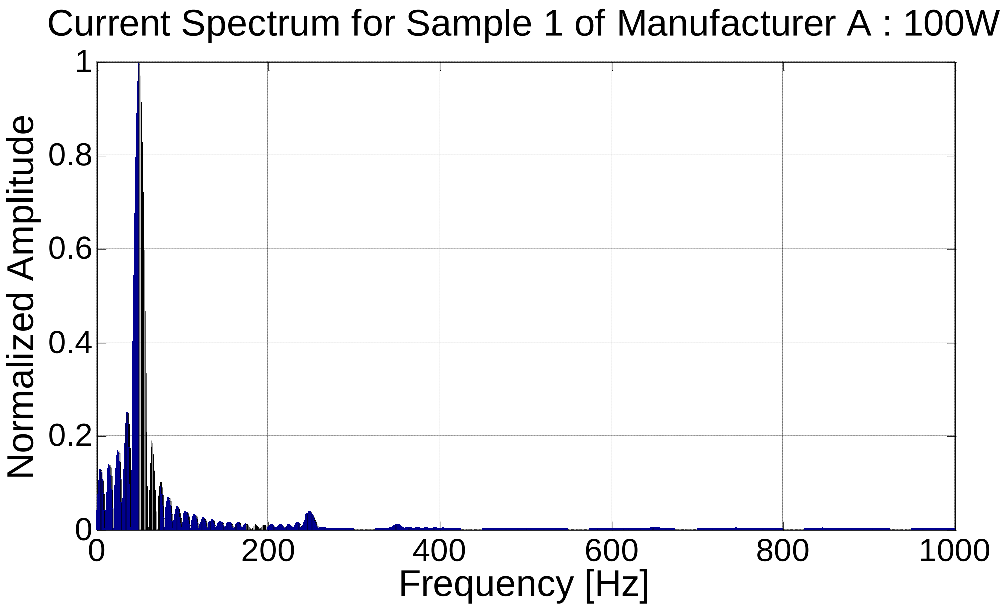

Figure 25: Current spectrum for the first 100 W IL sample from manufacturer A.

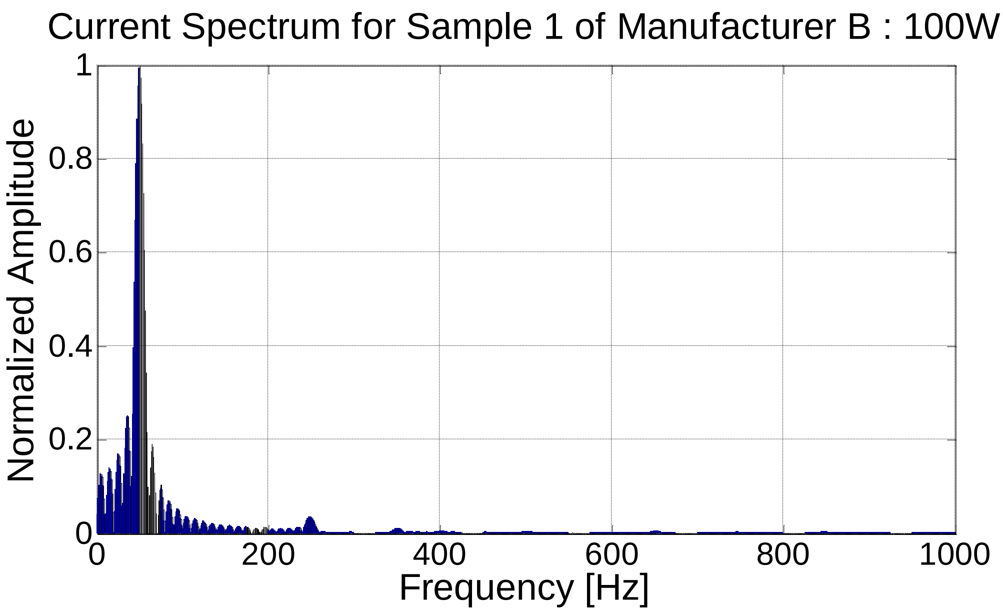

Figure 26: Current spectrum for the first 100 W IL sample from manufacturer B.

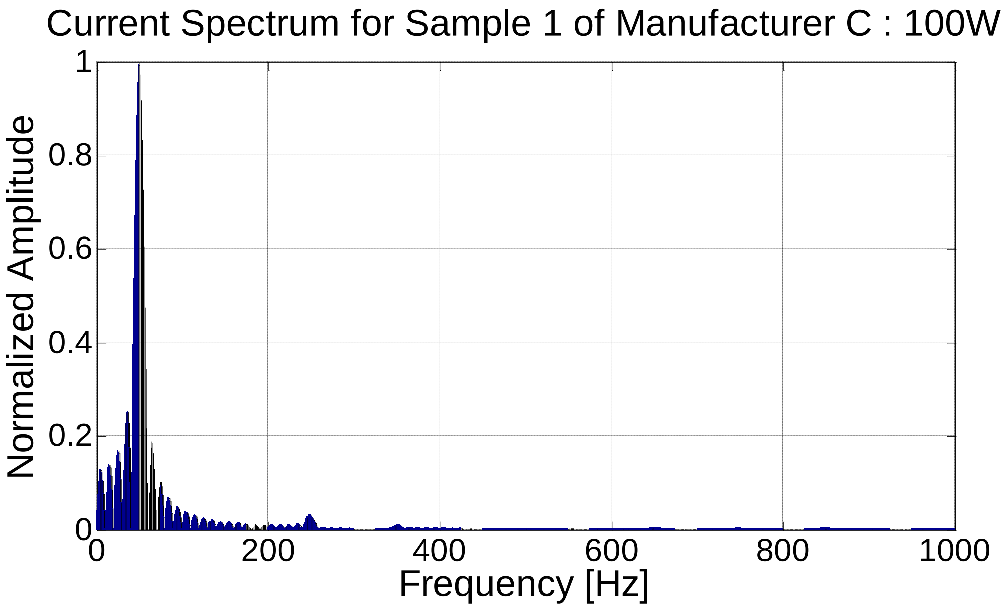

Figure 27: Current spectrum for the first 100 W IL sample from manufacturer C.

Table 5 summarises the magnitudes of the third harmonic components relative to the fundamental for each of the CFLs tested.

Table 5: Magnitudes of the 3rd harmonic components of the current waveforms of the ILs tested, for a supply voltage of 230V.

Manufacturer / Model	Power Rating [W]	Sample number	3rd Harmonic [%]
A	60	1	0.43907
		2	0.55304
		3	0.38279
	100	1	0.21439
		2	0.26575
		3	0.18525
B	60	1	0.25557
		2	0.55753
		3	0.37947
	100	1	0.20666
		2	0.18864
		3	0.16111
C	60	1	0.80674
		2	0.60327
		3	0.66964
	100	1	0.32431
		2	0.22559
		3	0.45089

Figure 28 to Figure 33 show the THDs of the supply current waveforms as a function of the RMS supply voltage for the IL samples tested.

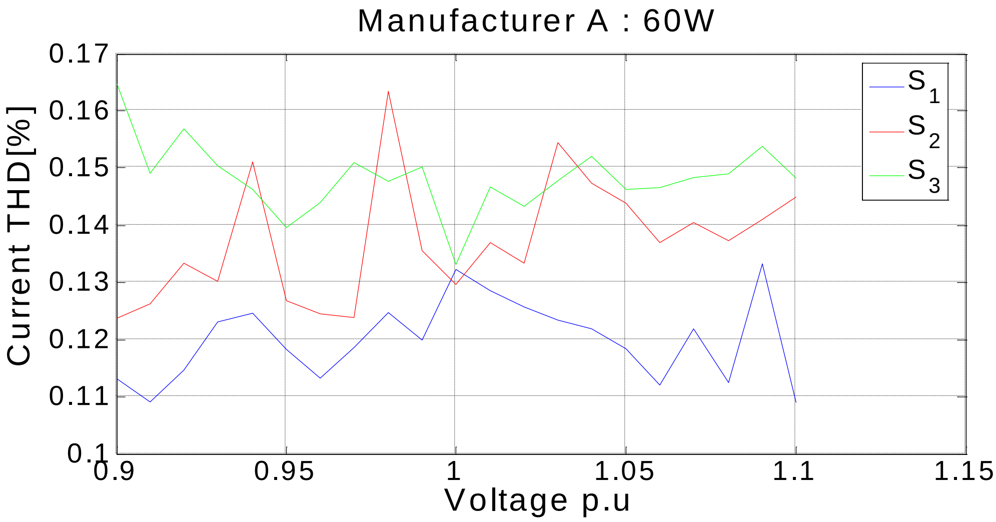

Figure 28: THD of the current waveform versus RMS supply voltage for the 60 W ILs from manufacturer A.

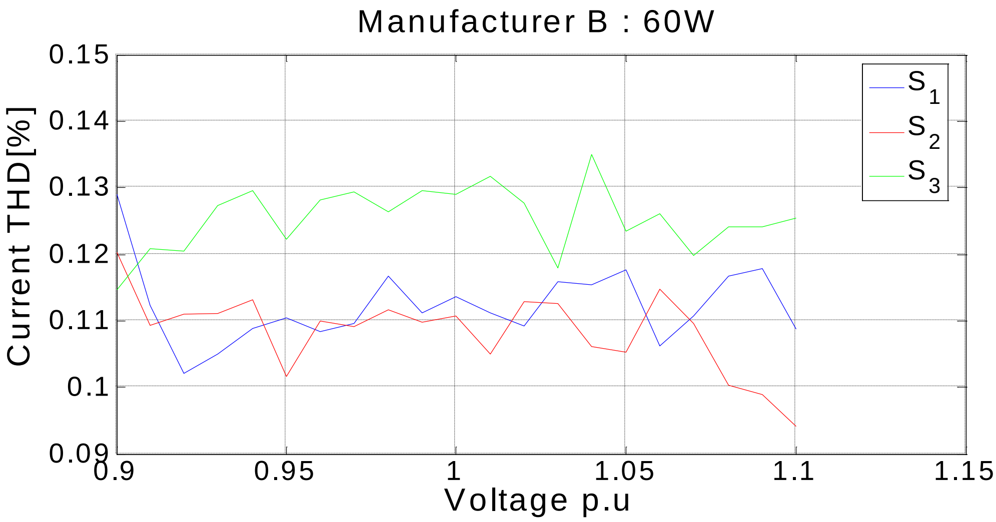

Figure 29: THD of the current waveform versus RMS supply voltage for the 60 W ILs from manufacturer B.

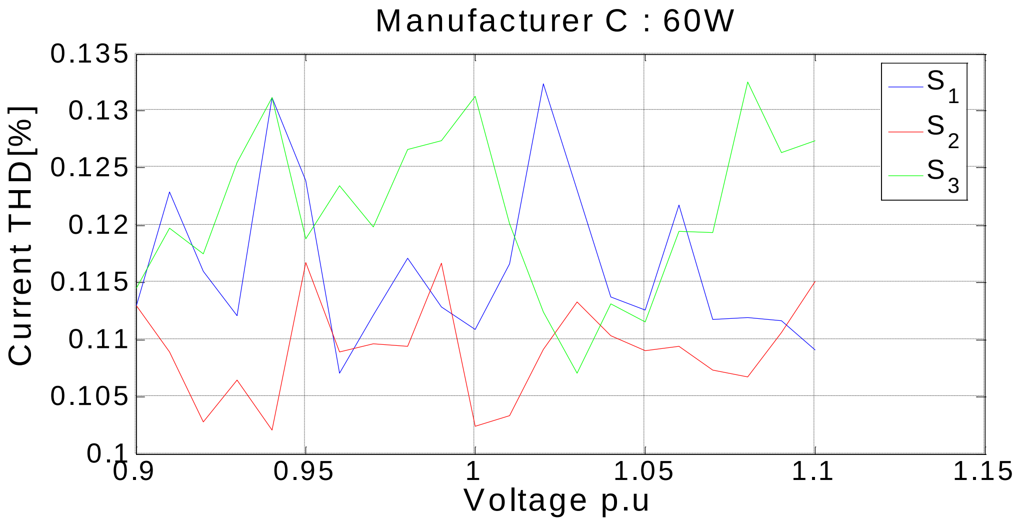

Figure 30: THD of the current waveform versus RMS supply voltage for the 60 W ILs from manufacturer C.

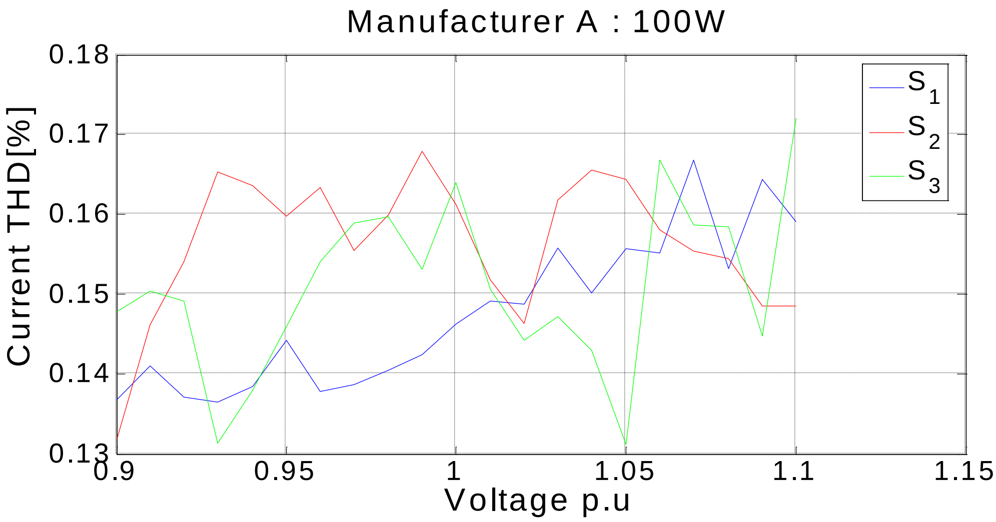

Figure 31: THD of the current waveformversus RMS supply voltage for the 100 W ILs from manufacturer A.

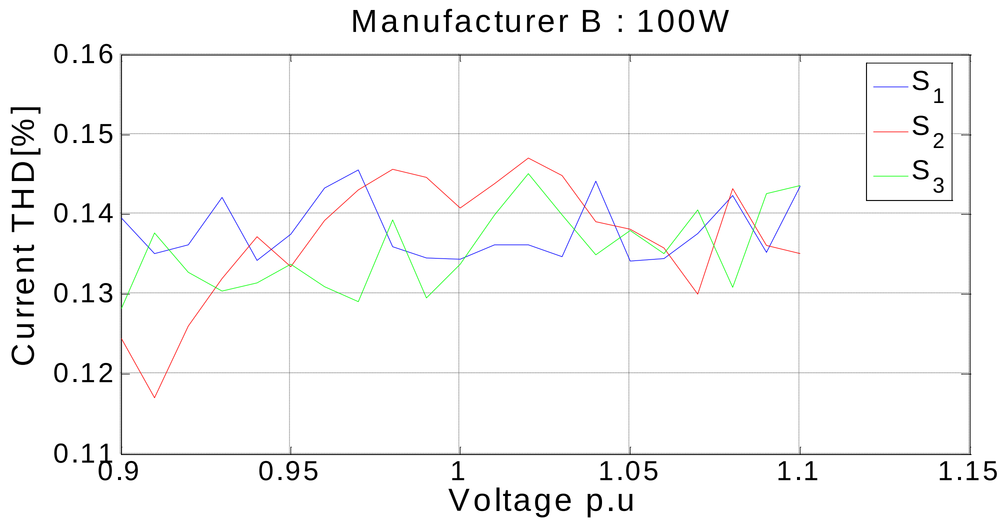

Figure 32: THD of the current waveform versus RMS supply voltage for the 100 W ILs from manufacturer B.

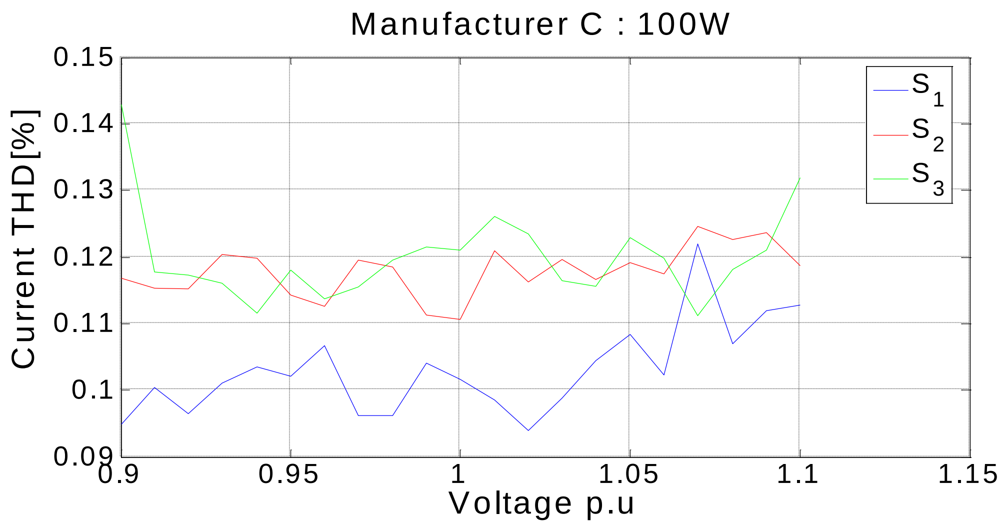

Figure 33: THD of the current waveform versus RMS supply voltage for the 100 W ILs from manufacturer C.

3.4.4 Zero sequence currents

3.4.4.1 Measurement results

Figure 34 to Figure 35 show the three-phase supply current and neutral current waveforms respectively for the 60 W IL from manufacturer A at a supply voltage of 230V. No significant neutral current is present. The other ILs tested yielded similar results.

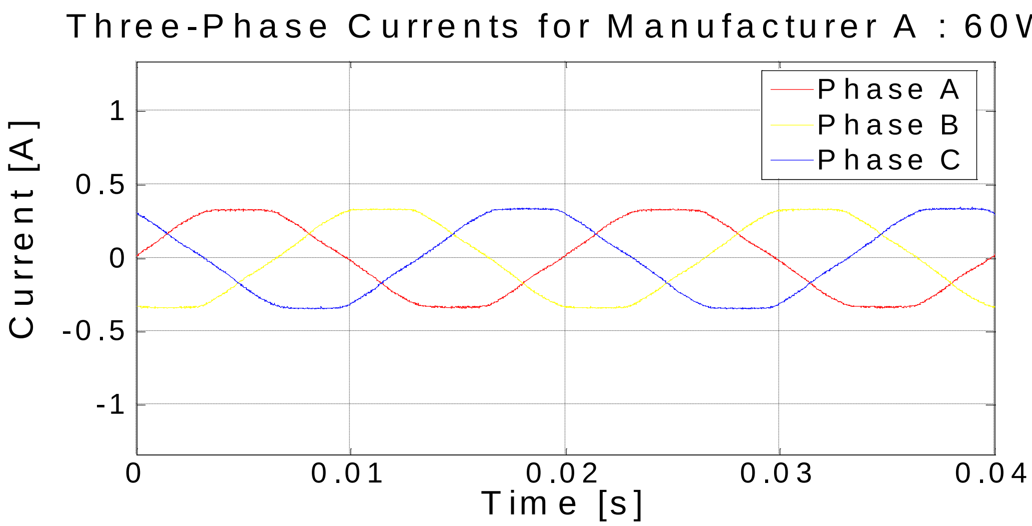

Figure 34: Three-phase current waveforms for the 60W ILs from manufacturer A.

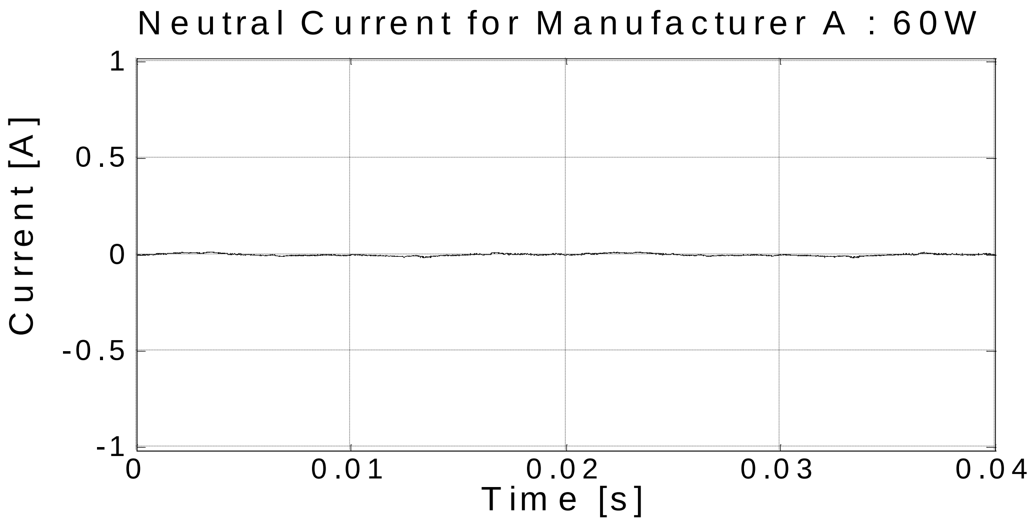

Figure 35: Neutral current waveform for the 60W ILs from manufacturer A.

Table 6 compares the phase currents and the neutral currents of the ILs tested in the investigation. The term "mixed" manufacturer refers to a three-phase test where a unit of a different manufacturer is used for each phase, i.e. phase A uses a unit from manufacturer A and phase B uses a unit from manufacturer B, etc.

Table 6: Summary of the RMS neutral currents and RMS phase currents for the ILs tested in the investigation.

Manufacturer / Model	Power Rating [W]	RMS Phase A Current [mA]	RMS Phase B Current [mA]	RMS Phase C Current [mA]	RMS Neutral Current [mA]
A	60	249.4	249.8	245.2	5.87
	100	406.8	406.7	408.6	6.17
B	60	246	241.2	245.2	4.27
	100	409.2	408.1	408.8	4.17
C	60	250.8	251.3	252.4	11.2

	100	414.8	415.8	428.4	15.63
Mixed (A,B,C)	60	-	-	-	11.81
Mixed (A,B,C)	100	-	-	-	11.07

3.5 Results for compact fluorescent lamps

3.5.1 Overview

A variety of commercial CFLs of different ratings and from different manufacturers were tested. In order to determine whether the test results are consistent for CFLs of the same rating from the same manufacturer, three samples of each rating per manufacturer were tested. Table 7 summarizes the subsection of the test results that are presented in this chapter.

Table 7: Summary of the CFLs considered in this chapter.

Manufacturer / Model	Power Rating [W]
A	14
	20
B	14
C	14
	20
D	20

3.5.2 Voltage dependency measurement results

Appendix A contains all the data relevant to this chapter.

3.5.2.1 Modelling of the voltage dependency of the active power consumption of CFLs

Table 8 summarizes the polynomial curve fitting models determined for each of the CFL types evaluated.

Table 8: CFL power consumption models derived.

Manufacturer/Model	Power Rating [W]	Active power model [W]
A	14	$0.0571V - 0.2671$
	20	$0.1219V - 9.3345$
B	14	$0.0662V - 3.2723$
C	14	$0.0562V - 0.4453$
	20	$0.0508V + 5.5081$
D	20	$0.0781V + 0.3014$

Figure 36 to Figure 41 compare the active power versus RMS supply voltage responses of the models (M) to the original measurements obtained for each sample. The correlations of the measurements between the different models are generally good. The measurements from the different manufacturers show the same trend, i.e. an increase in active power consumption for an increase in supply voltage. The results for the samples of the same rating from the same manufacturer show that there is generally a moderate difference between the samples.

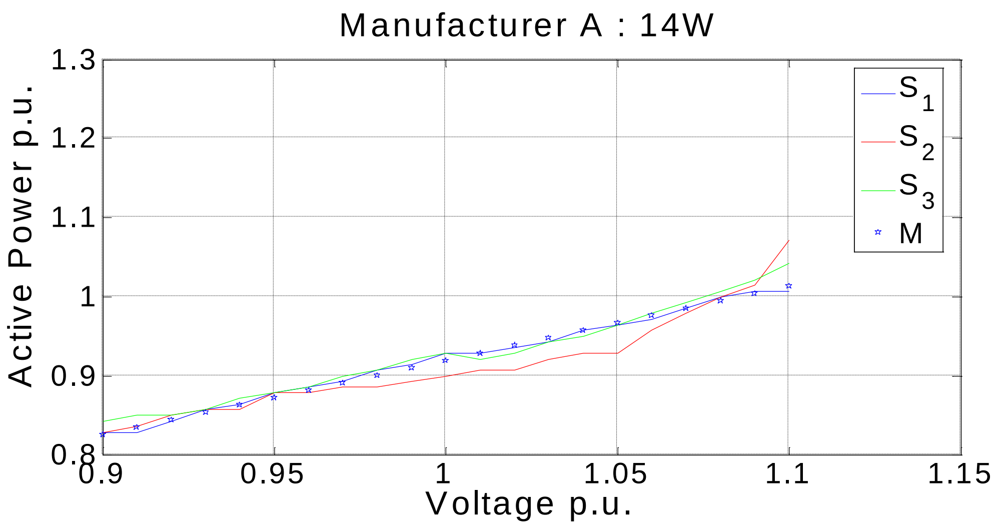

Figure 36: Measured and modelled active power consumption versus RMS supply voltage for the 14 W CFL samples from manufacturer A.

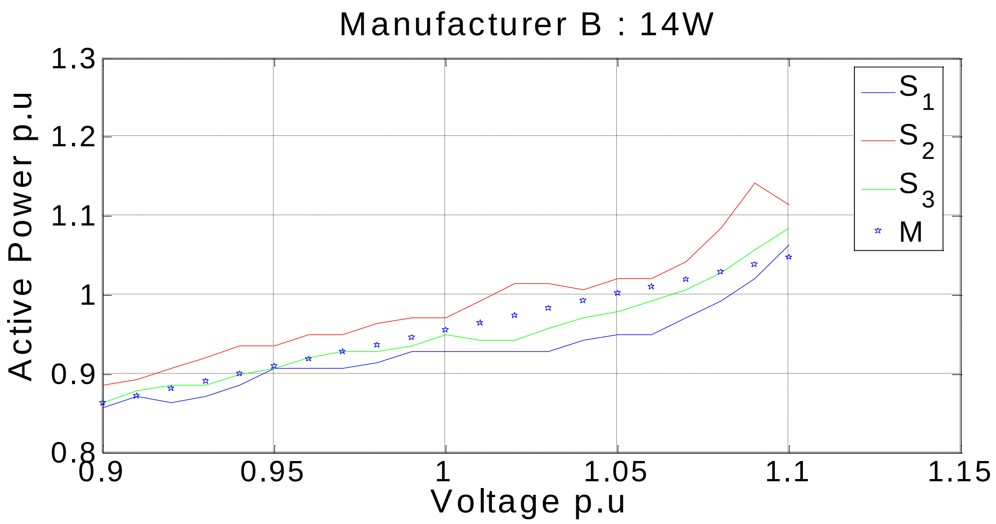

Figure 37: Measured and modelled active power consumption versus RMS supply voltage for the 14 W CFL samples from manufacturer B.

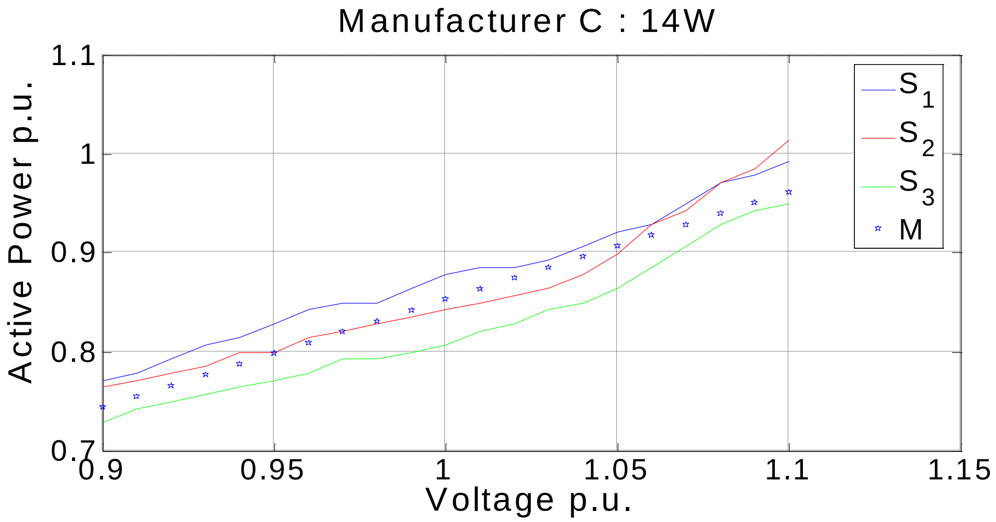

Figure 38: Measured and modelled active power consumption versus RMS supply voltage for the 14 W CFL samples from manufacturer C.

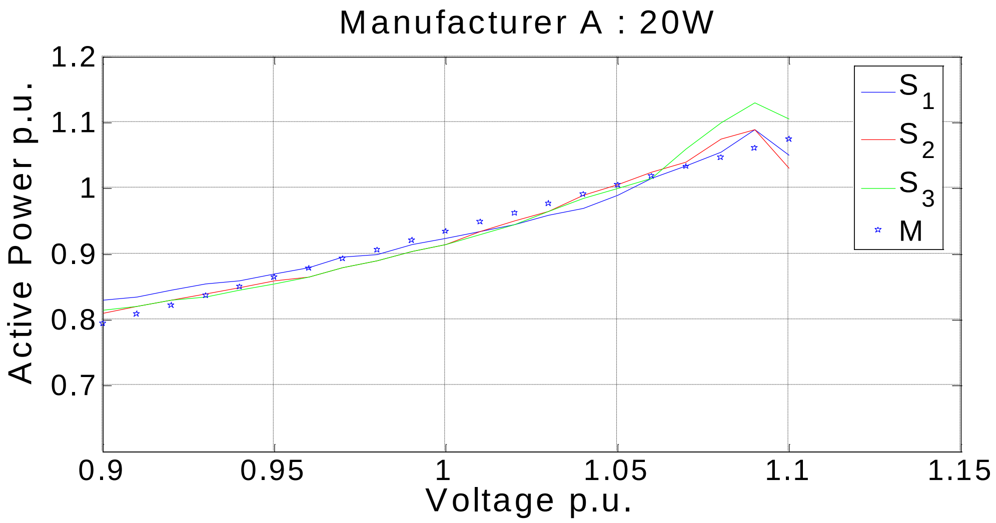

Figure 39: Measured and modelled active power consumption versus RMS supply voltage for the 20 W CFL samples from manufacturer A.

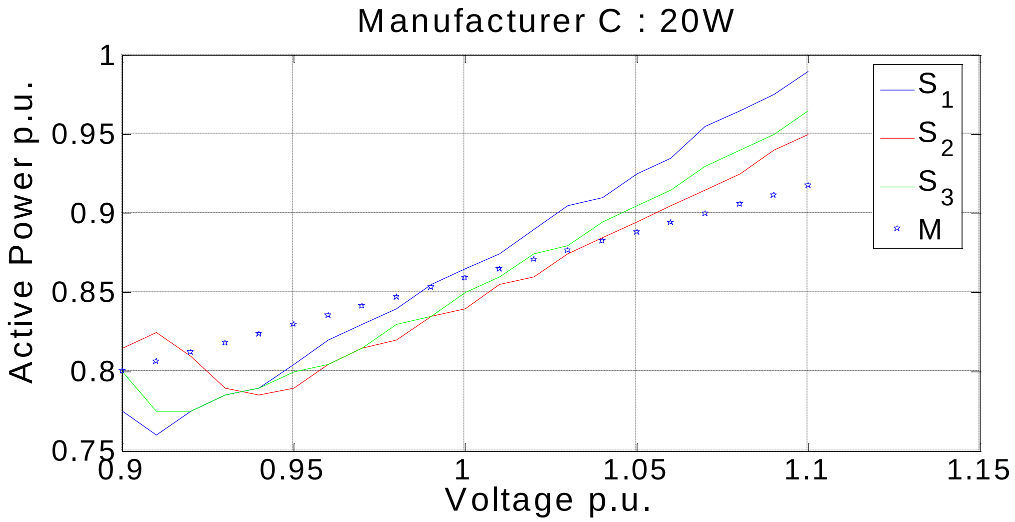

Figure 40: Measured and modelled active power consumption versus RMS supply voltage for the 20 W CFL samples from manufacturer C.

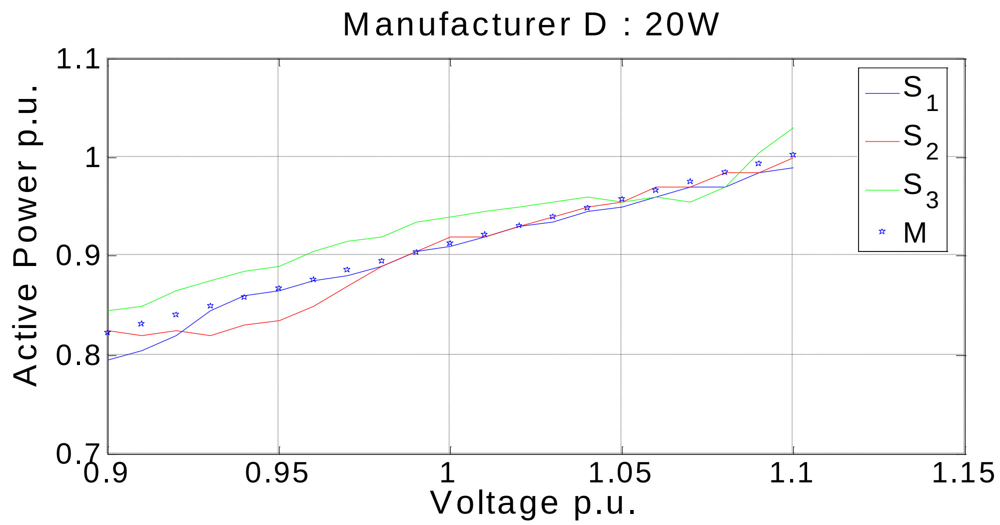

Figure 41: Measured and modelled active power consumption versus RMS supply voltage for the 20 W CFL samples from manufacturer D.

3.5.3 Waveform and spectral analysis

3.5.3.1 Supply voltage and current waveforms

Figure 42 shows a typical example of the supply voltage and current waveforms recorded for the test samples. The current waveform is highly distorted and exhibits the properties of a full-wave rectifier with an active load. The current waveform is symmetrical for the positive and negative halves of the supply voltage waveform, thus no even harmonic components are expected.

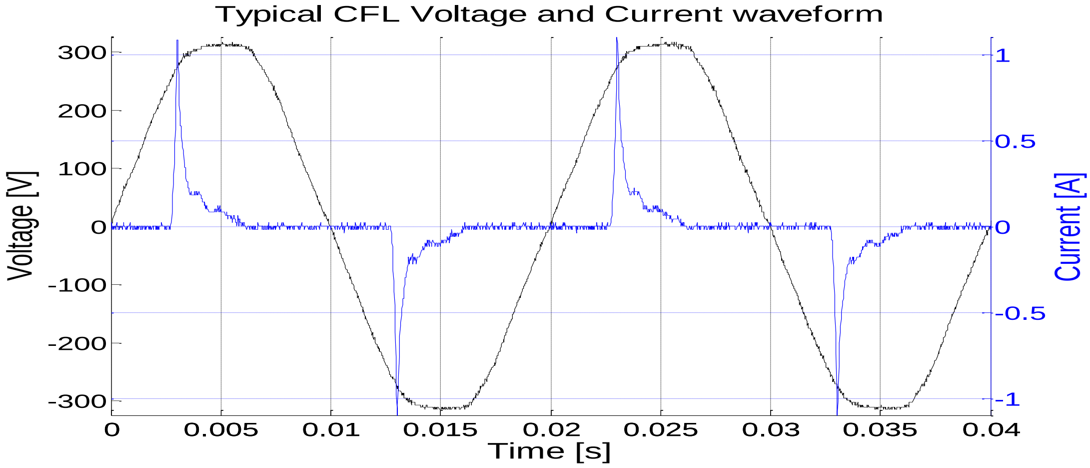

Figure 42: Typical supply voltage and current waveforms for a 14W CFL.

3.5.3.2 Harmonic content of the supply current

Figure 43 to Figure 47 shows the harmonic spectrum of the current waveform for the CFL sample 1 of each of the manufacturers considered in this chapter. The current spectrums exhibit large uneven harmonics.

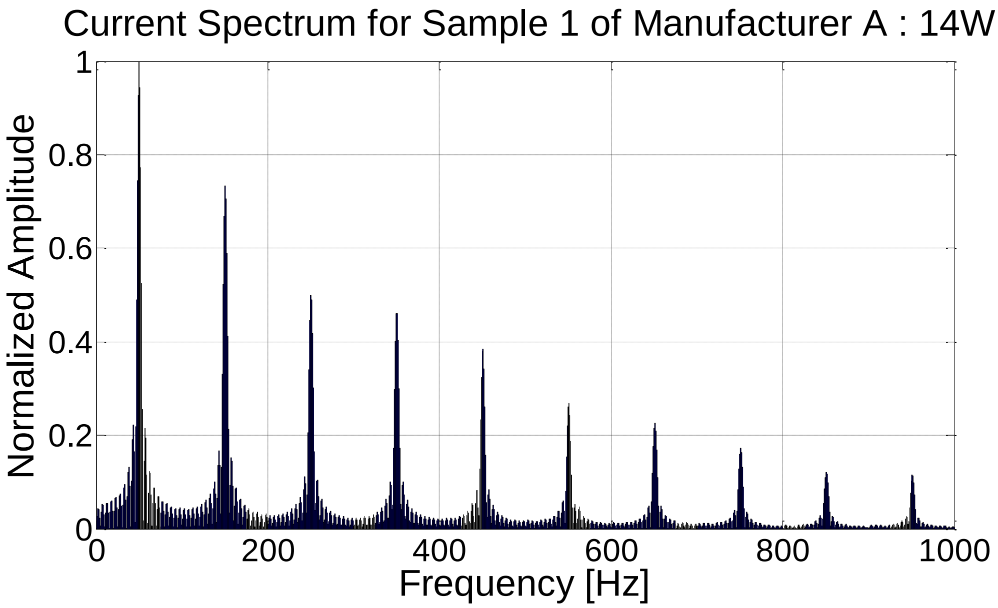

Figure 43: Current spectrum for the first 14W CFL sample from manufacturer A.

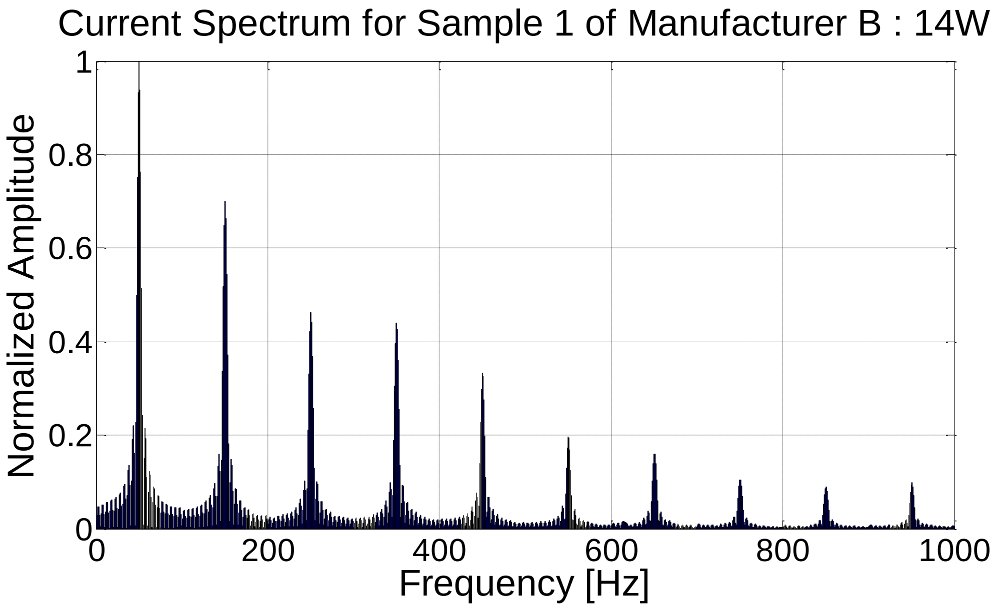

Figure 44: Current spectrum for the first 14W CFL sample from manufacturer B.

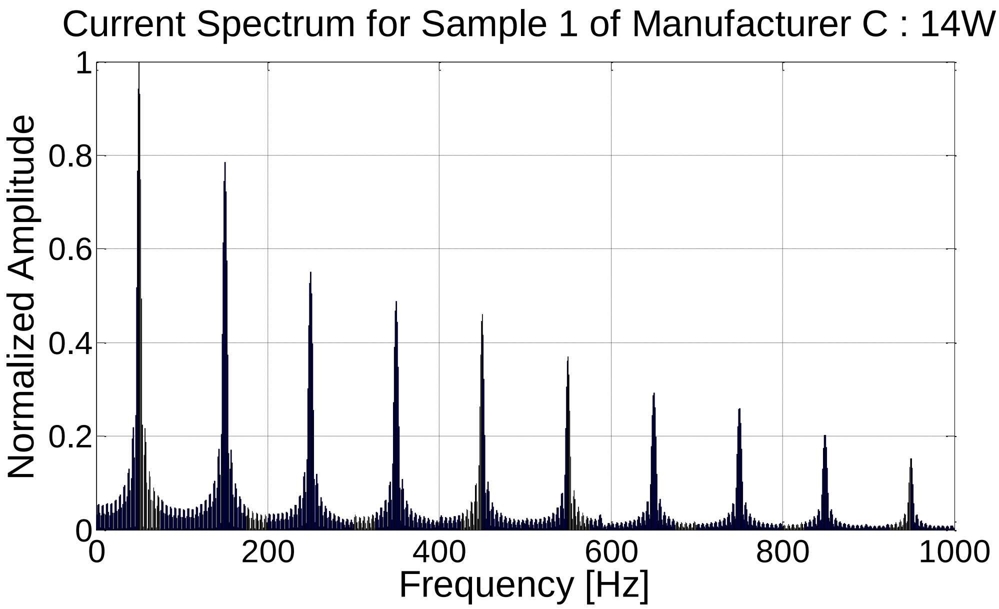

Figure 45: Current spectrum for the first 14W CFL sample from manufacturer C.

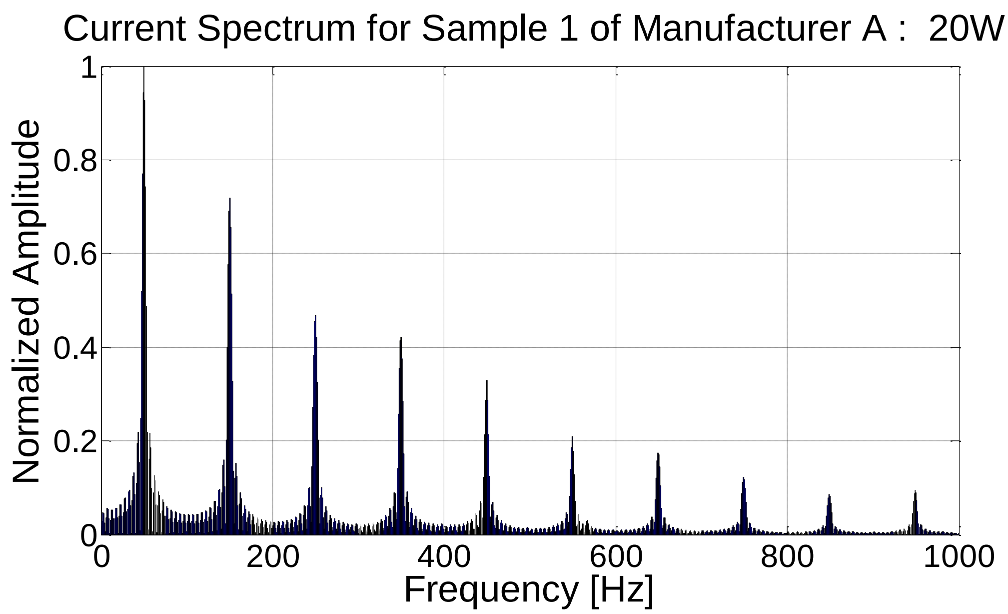

Figure 46: Current spectrum for the first 20W CFL sample from manufacturer A.

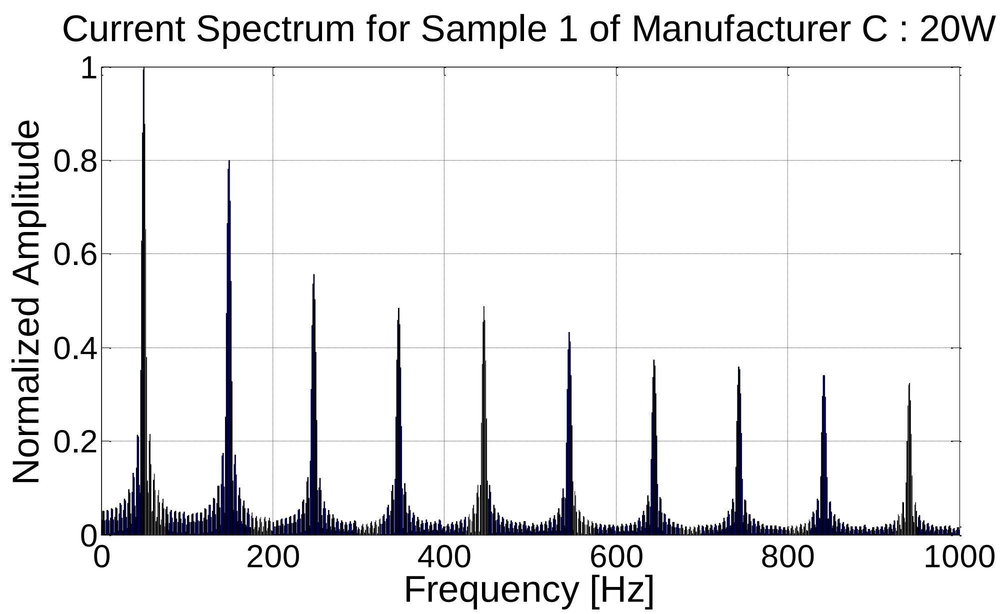

Figure 47: Current spectrum for the first 20W CFL sample from manufacturer C.

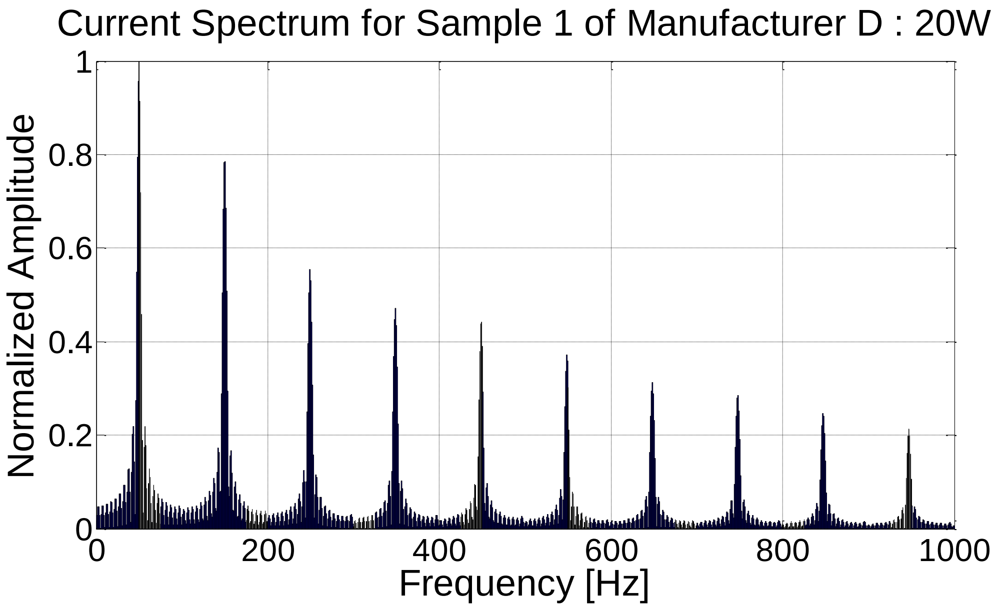

Figure 48: Current spectrum for the first 20W CFL sample from manufacturer D.

Table 9 illustrates the magnitude of the third harmonic relative to the fundamental for each of the tested CFLs.

Table 9: Magnitudes of the 3rd harmonics, of the CFLs considered in this chapter, for a supply voltage of 230V.

Manufacturer / Model	Power Rating [W]	Sample number	3rd Harmonic [%]
A	14	1	73.38
		2	71.98
		3	71.33
	20	1	71.94
		2	71.41
		3	70.87
B	14	1	70.04
		2	70.41
		3	70.75
C	14	1	78.43
		2	78.83
		3	79.22
	20	1	71.24
		2	79.36
		3	80.38
D	20	1	78.44
		2	78.11
		3	75.21

Figure 49 to Figure 54 show the THD of the supply current waveforms respectively as a function of the RMS supply voltage for various CFL samples tested.

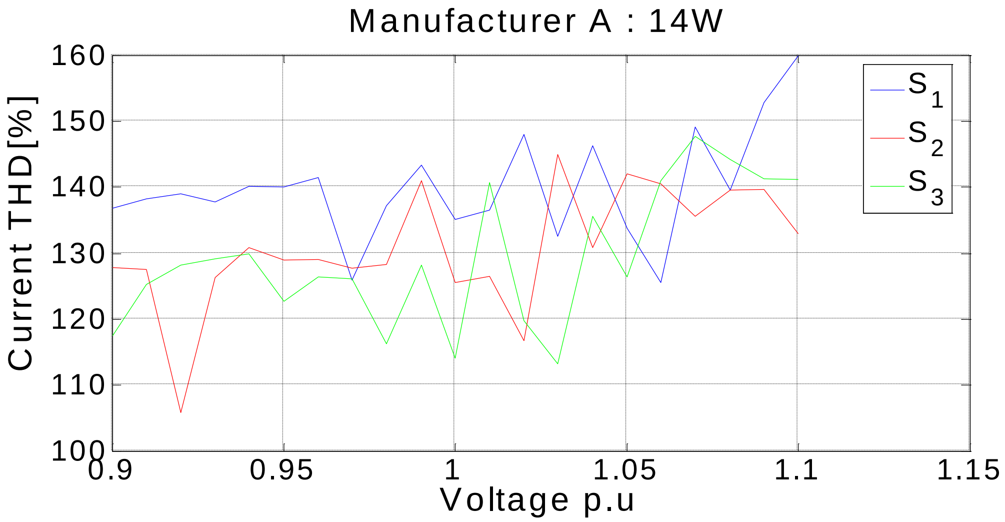

Figure 49: THD of the current waveform versus RMS supply voltage for the 14W CFLs from manufacturer A.

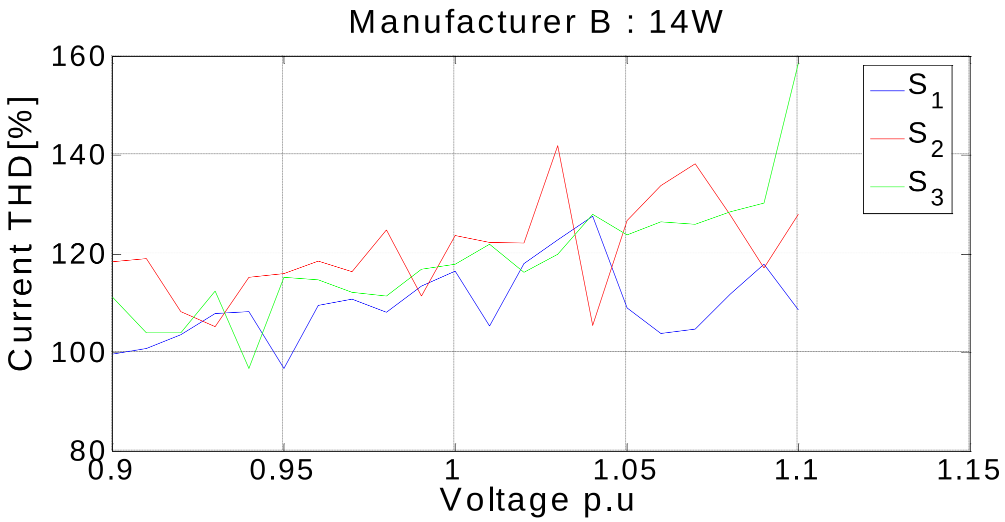

Figure 50: THD of the current waveform versus RMS supply voltage for the 14W CFLs from manufacturer B.

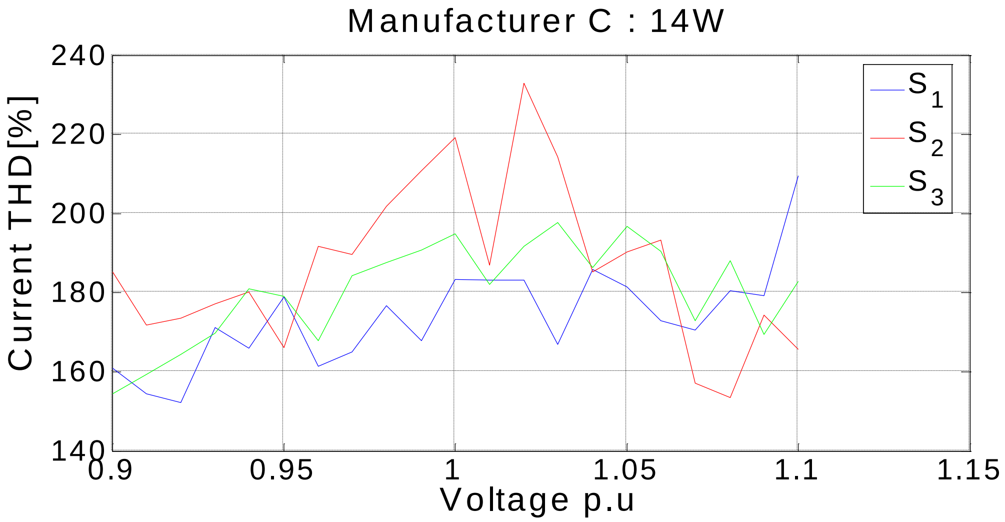

Figure 51: THD of the current waveform versus RMS supply voltage for the 14W CFLs from manufacturer C.

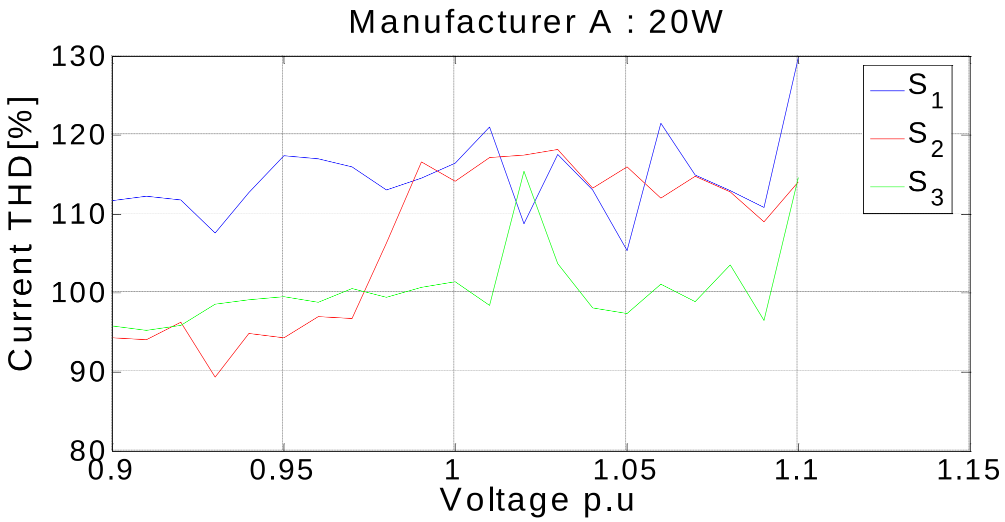

Figure 52: THD of the current waveform versus RMS supply voltage for the 20W CFLs from manufacturer A.

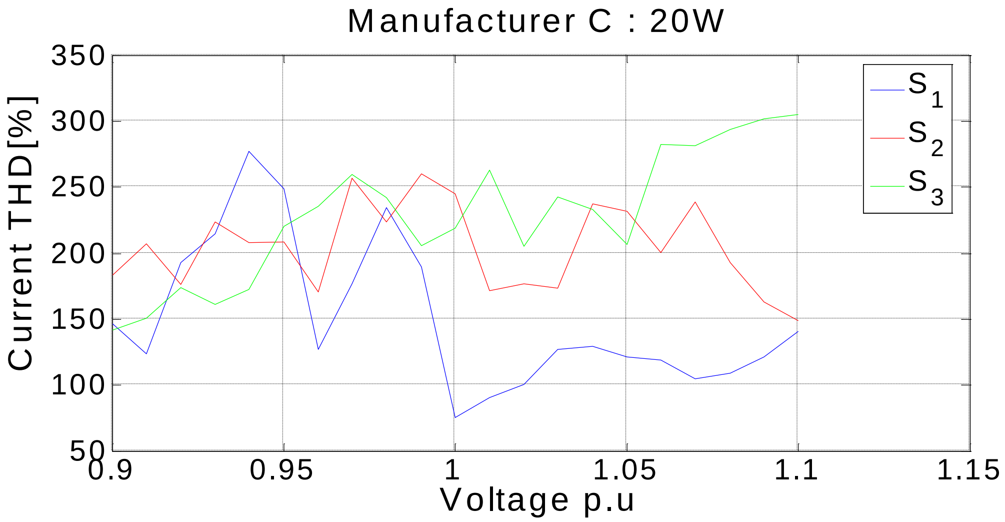

Figure 53: THD of the current waveform versus RMS supply voltage for the 20W CFLs from manufacturer C.

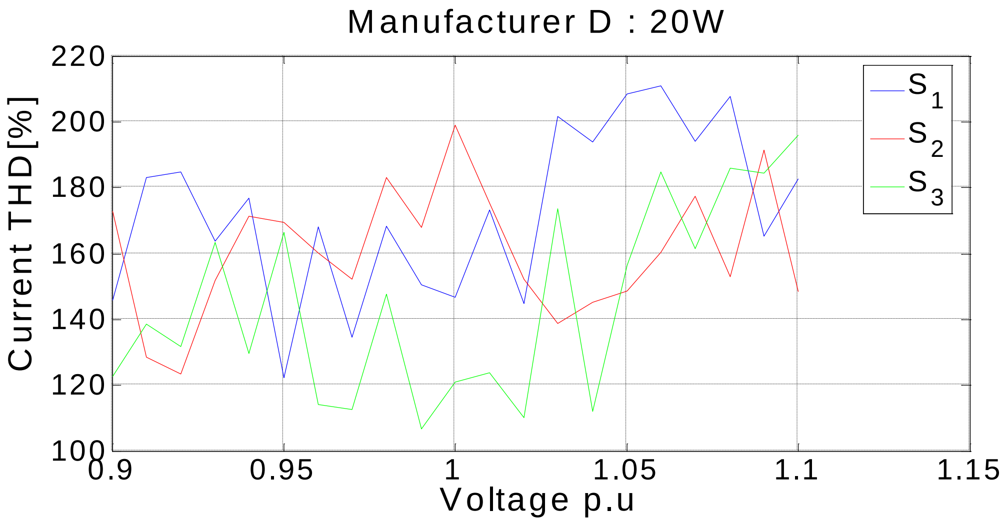

Figure 54: THD of the current waveform versus RMS supply voltage for the 20W CFLs from manufacturer D.

3.5.4 Zero sequence currents

3.5.4.1 Measurement results

Figure 55 to Figure 66 show the results for the three-phase supply current and neutral current waveforms respectively, at a supply voltage of 230V, for the CFLs considered in this chapter. The three-phase supply current yields a large neutral current component, as expected based on the time-domain and frequency-domain properties of the phase waveforms.

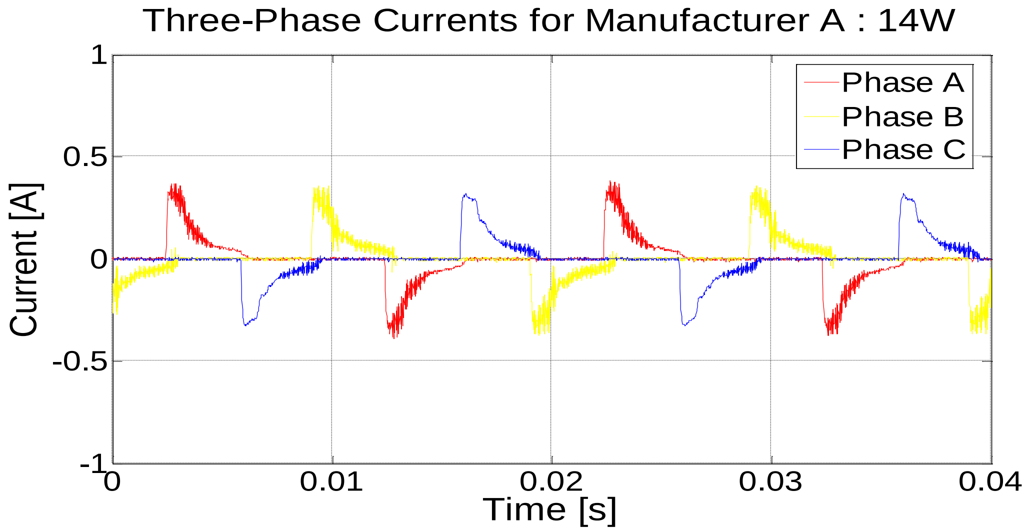

Figure 55: Three-phase current waveforms for the 14W CFLs from manufacturer A.

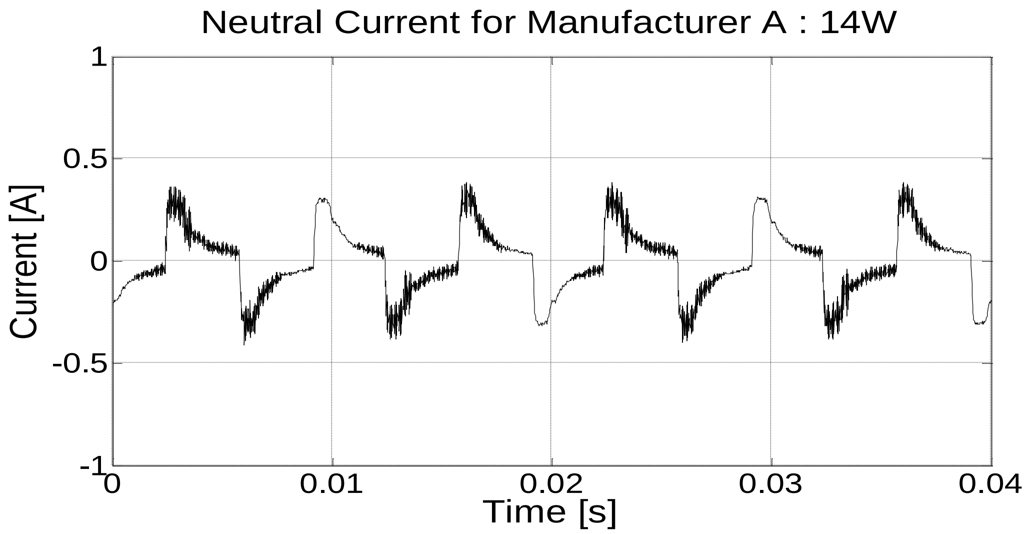

Figure 56: Neutral current waveform for the 14W CFLs from manufacturer A.

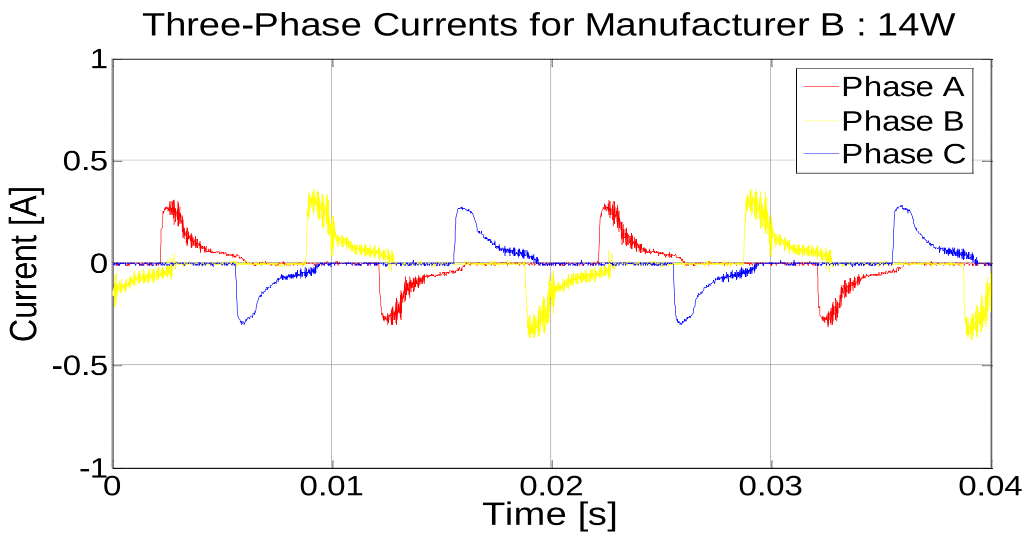

Figure 57: Three-phase current waveforms for the 14W CFLs from manufacturer B.

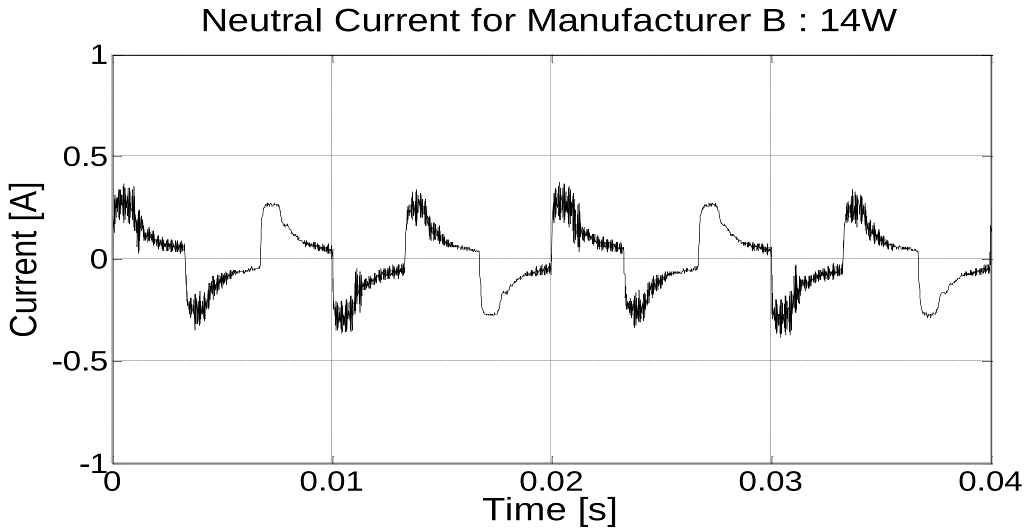

Figure 58: Neutral current waveform for the 14W CFLs from manufacturer B.

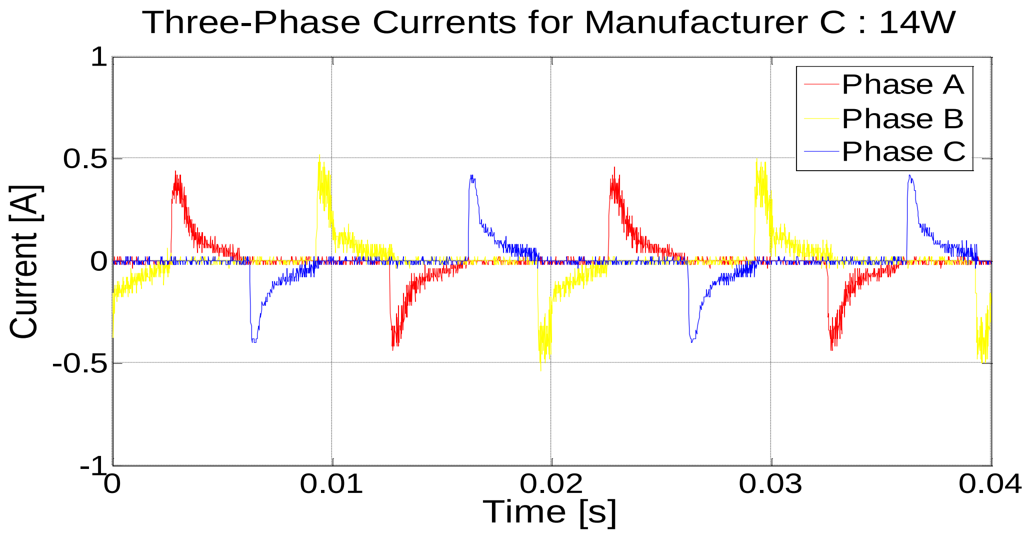

Figure 59: Three-phase current waveforms for the 14W CFLs from manufacturer C.

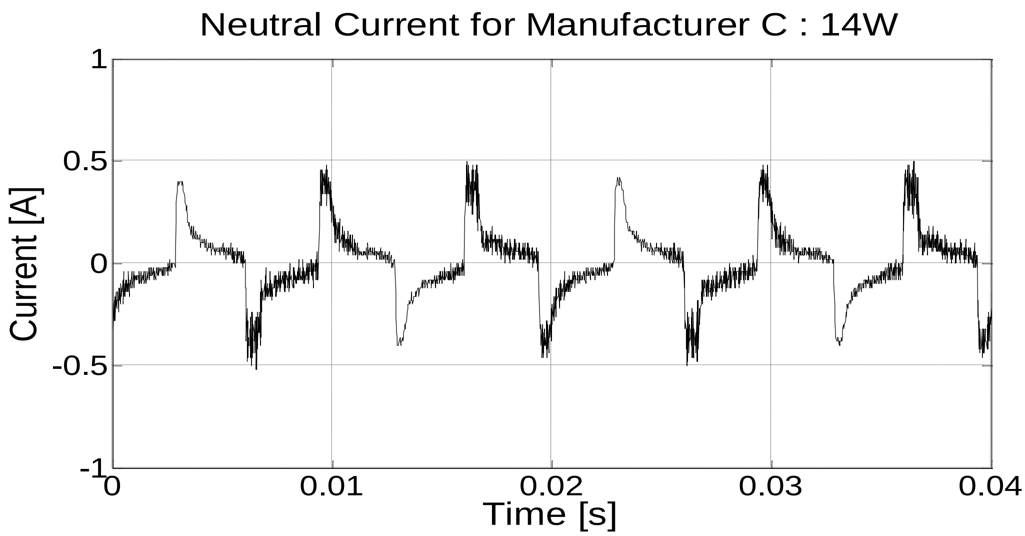

Figure 60: Neutral current waveform for the 14W CFLs from manufacturer C.

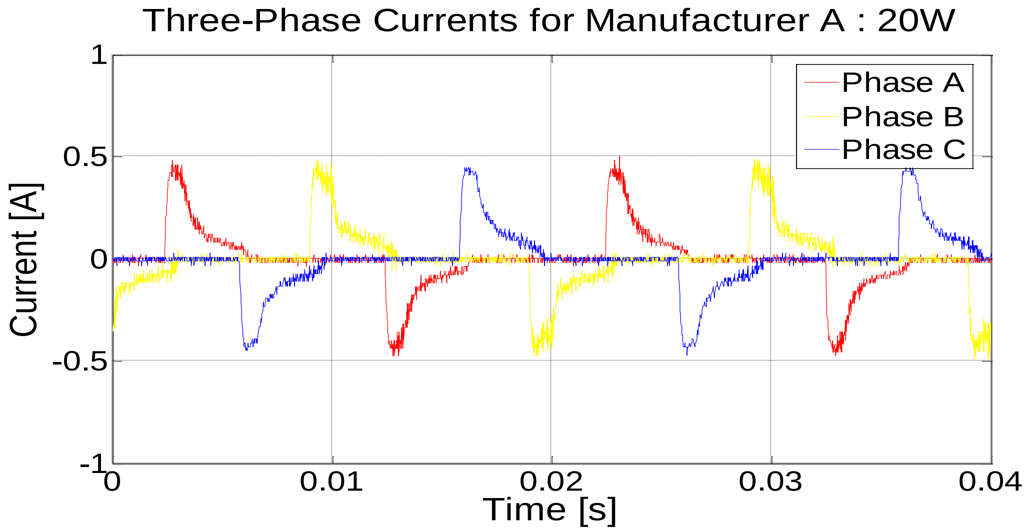

Figure 61 : Three-phase current waveforms for the 20W CFLs from manufacturer A.

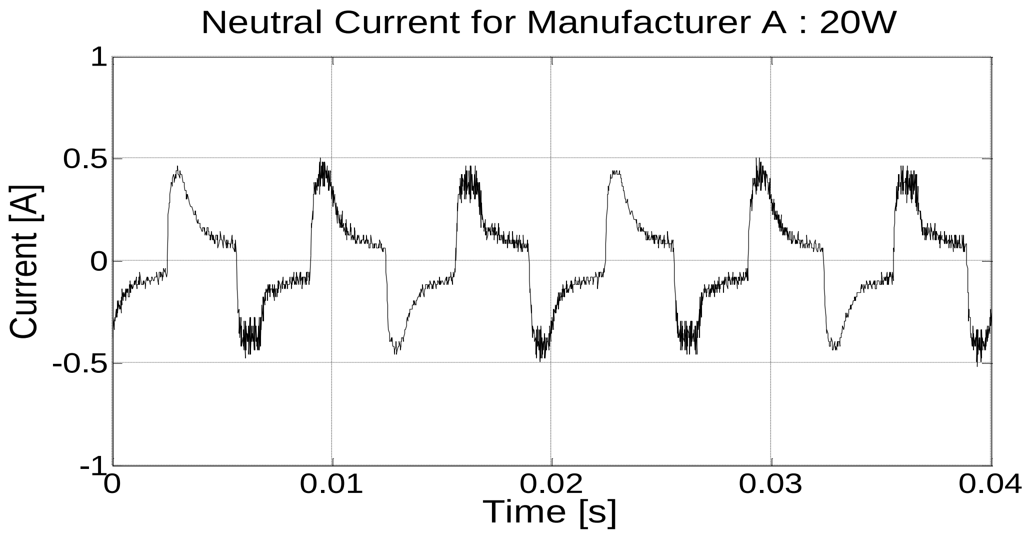

Figure 62: Neutral current waveform for the 20W CFLs from manufacturer A.

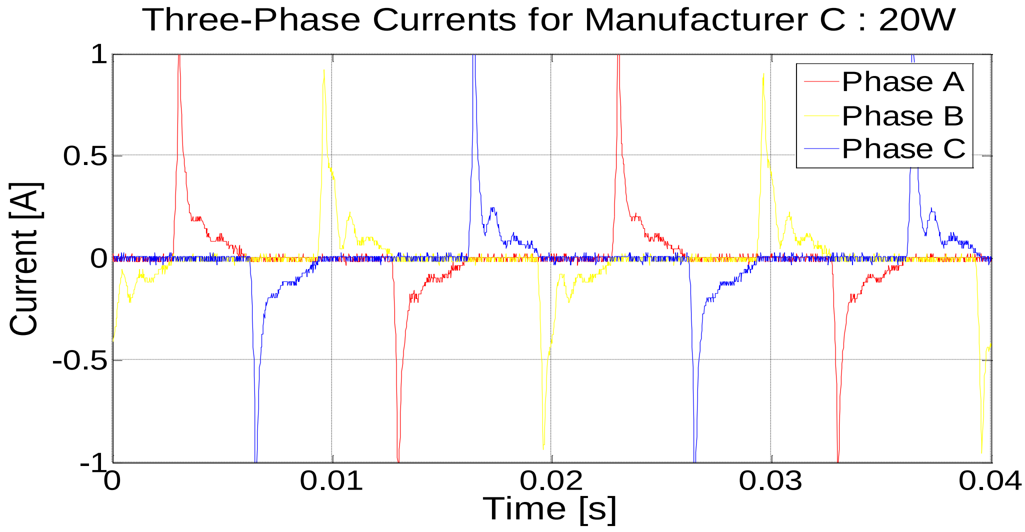

Figure 63: Three-phase current waveforms for the 20W CFLs from manufacturer C.

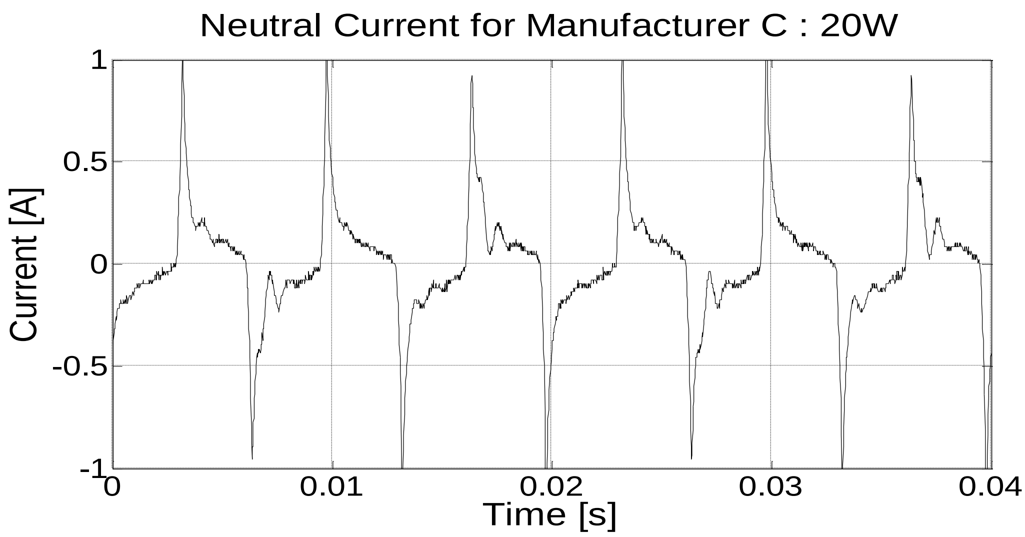

Figure 64: Neutral current waveform for the 20W CFLs from manufacturer C.

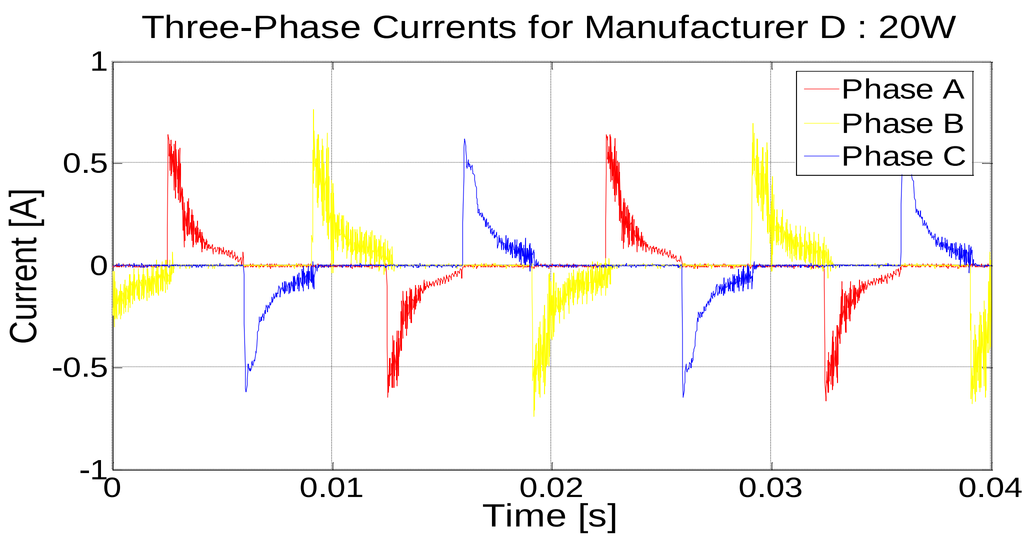

Figure 65: Three-phase current waveforms for the 20W CFLs from manufacturer D.

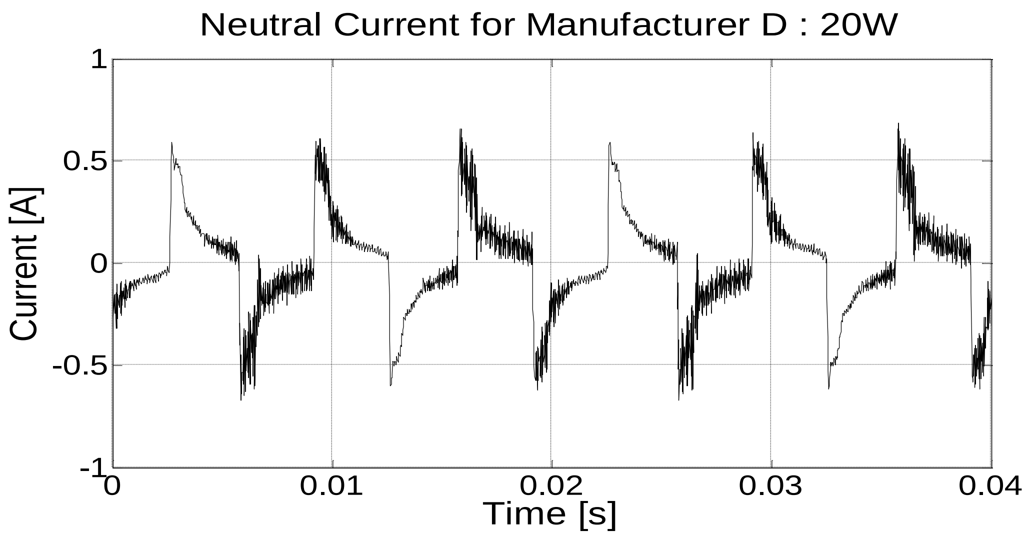

Figure 66: Neutral current waveform for the 20W CFLs from manufacturer D.

Figure 67 to Figure 70 show the results for the three-phase supply current and neutral current waveforms respectively for 14W and 20W CFLs where the manufacturers are mixed, i.e. one sample of Manufacturer A, B and C/D on each phase.

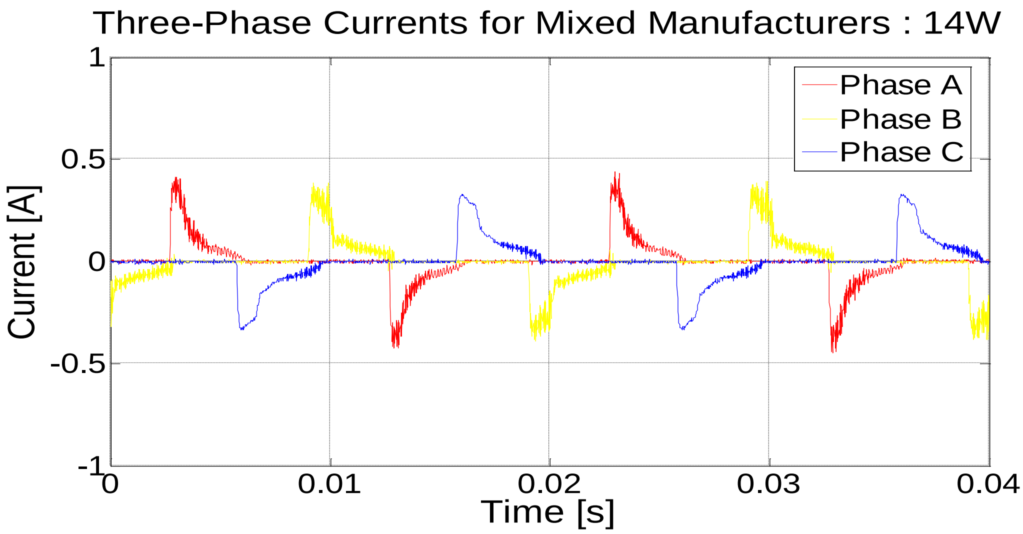

Figure 67: Three-phase current waveforms s for the 14W CFLs from mixed manufacturers.

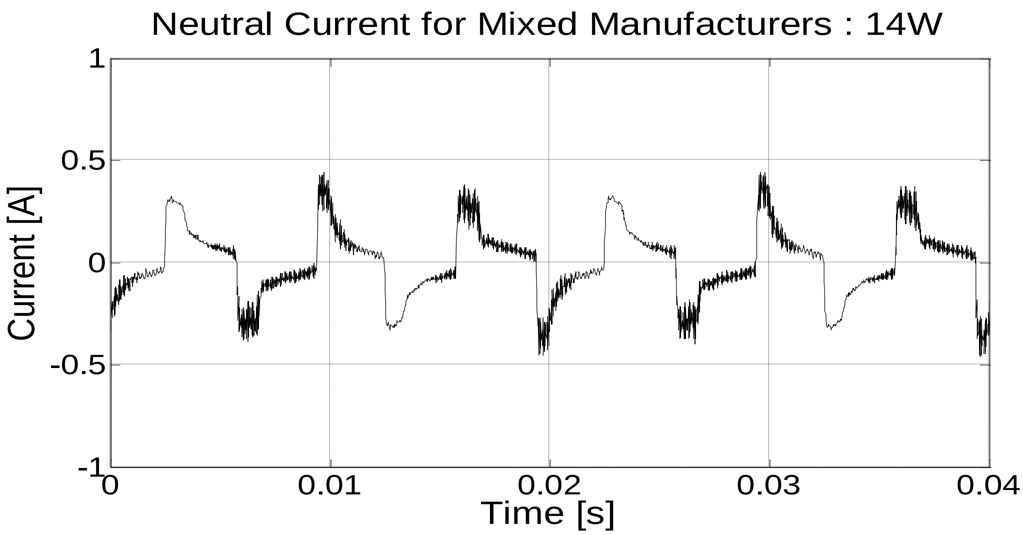

Figure 68: Neural current waveform for the 14W CFLs from mixed manufacturers.

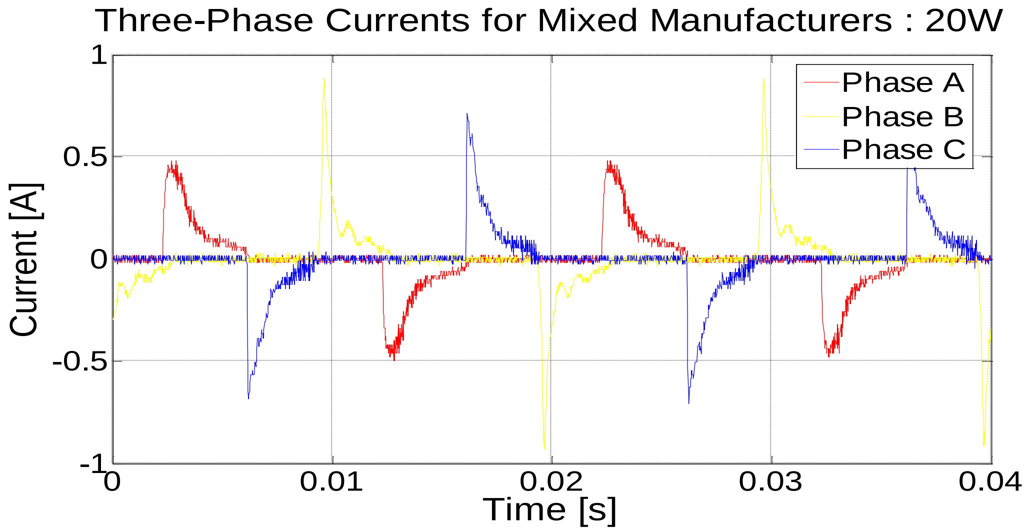

Figure 69: Three-phase current waveforms for the 20W CFLs from mixed manufacturers.

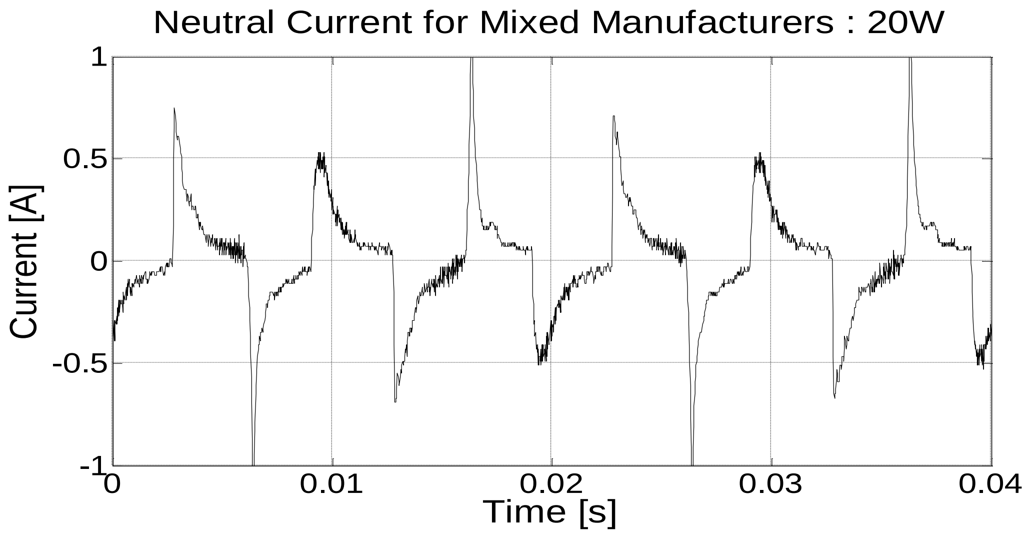

Figure 70: Neutral current waveform for the 20W CFLs from mixed manufacturers.

Table 10 contains a comparison between the phase currents and the neutral currents of the CFLs considered in this chapter.

Table 10: RMS neutral current vs. RMS phase current for CFLs considered in this chapter.

Manufacturer / Model	Power Rating [W]	RMS Phase A Current [mA]	RMS Phase B Current [mA]	RMS Phase C Current [mA]	RMS Neutral Current [mA]
A	14	96.3	91.3	94.7	168.1
	20	129.8	128.4	129.0	232.3
B	14	91.1	96.0	94.0	156.1
C	14	94.7	99.2	91.1	174.4
	20	149.8	143.9	148.0	285.1
D	20	148.6	151.4	148.0	250.2
Mixed (A,B,C)	14	-	-	-	164.1
Mixed (A,C,D)	20	-	-	-	255.0

3.6 Results for tubular fluorescent lamps

3.6.1 Overview

A variety of commercial TFLs of different ratings and from different manufacturers were tested. In order to determine whether the test results are consistent for TFLs of the same rating from the same manufacturer, three samples of each rating per manufacturer were tested. Table 11 summarizes the subsection of the test results that are presented in this chapter.

Table 11: Summary of the TFLs considered in this chapter.

Manufacturer / Model	Ballast type	Ballast manufacturer	Power Rating [W]
A	Magnetic	alpha	36
			58
	Electronic	alpha	36
			58
B	Magnetic	alpha	36
			58
	Electronic	alpha	36
			58

3.6.2 Voltage dependency measurement results for TFLs with magnetic ballasts

Appendix A contains all the data relevant to this chapter.

3.6.2.1 Modelling of the voltage dependency of the active power consumption of TFLs with magnetic ballasts

Table 12 summarizes the polynomial curve fitting models determined for each of the TFL types evaluated.

Table 12: TFLs with magnetic ballasts power consumption models derived.

Manufacturer / Model	Ballast type	Ballast manufacturer	Power Rating [W]	Active power model [W]
A	Magnetic	alpha	36	$0.39488V - 47.402$
			58	$0.68748V - 91.088$
B	Magnetic	alpha	36	$0.39966V - 48.262$
			58	$0.66223V - 84.739$

Figure 71 to Figure 74 compare the active power versus RMS supply voltage responses of the models (M) to the original measurements obtained for each TFL sample. The correlations of the measurements between the different models are generally good. The results for the samples of the same rating from the same manufacturer vary from almost identical to a spread of approximately 5% as for the 58W units.

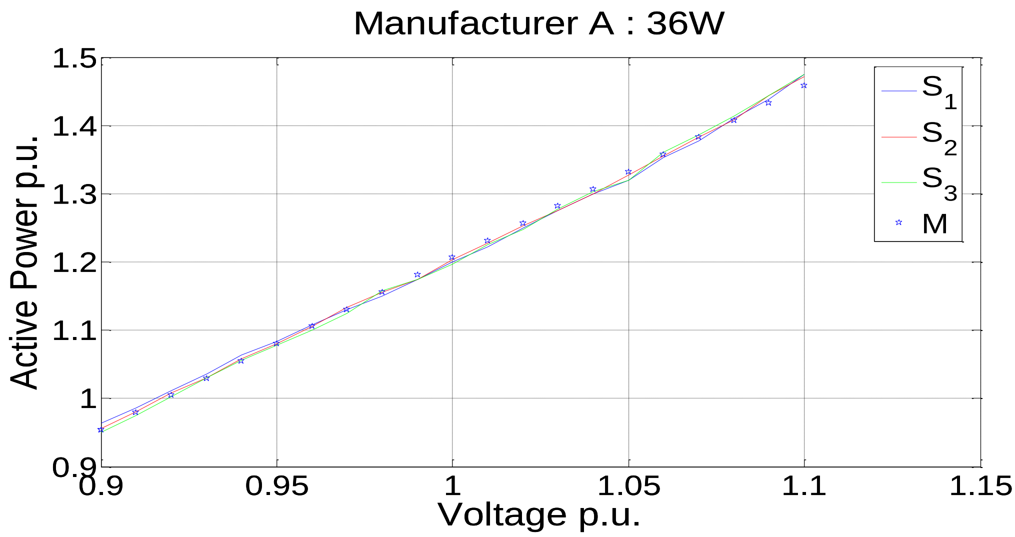

Figure 71: Measured and modelled active power consumption versus RMS supply voltage for the 36 W TFL samples from manufacturer A and magnetic ballast alpha.

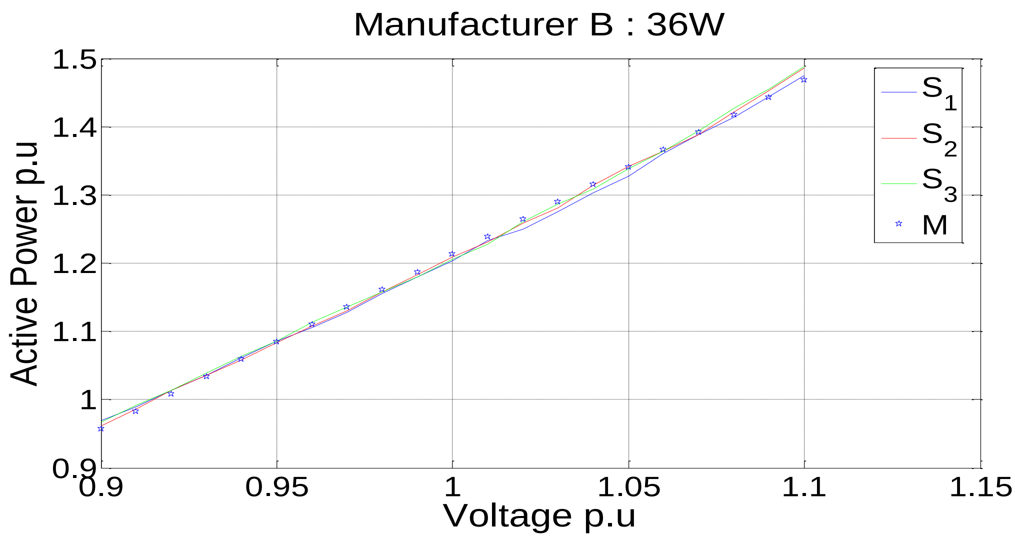

Figure 72: Measured and modelled active power consumption versus RMS supply voltage for the 36 W TFL samples from manufacturer B and magnetic ballast alpha.

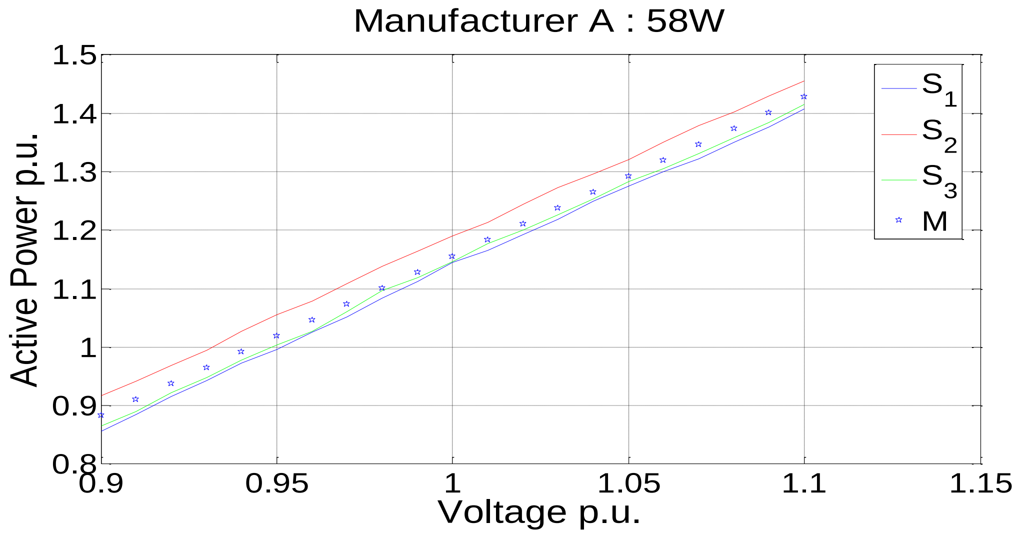

Figure 73: Measured and modelled active power consumption versus RMS supply voltage for the 58 W TFL samples from manufacturer A and magnetic ballast alpha.

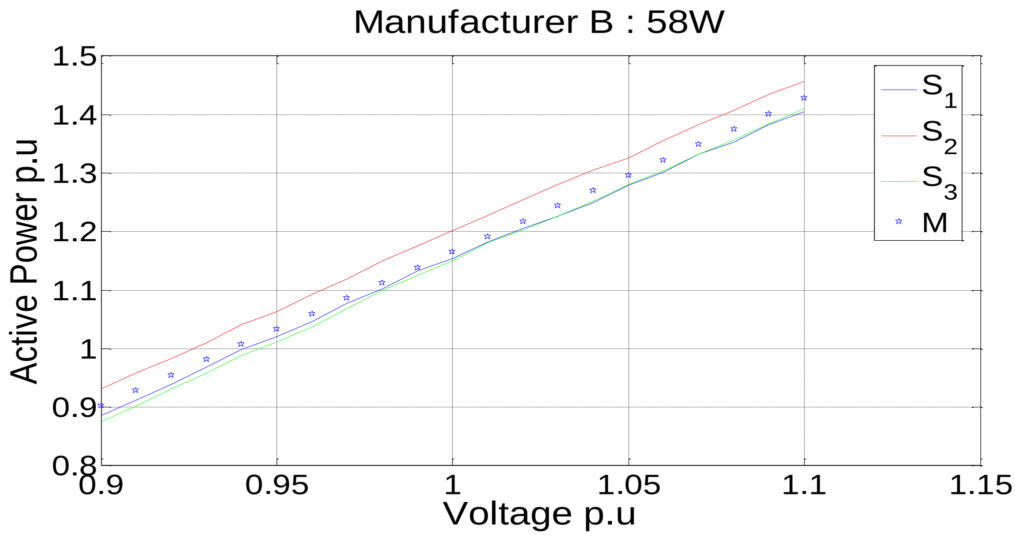

Figure 74: Measured and modelled active power consumption versus RMS supply voltage for the 58 W TFL samples from manufacturer B and magnetic ballast alpha.

3.6.3 Waveform and spectral analysis for TFLs with magnetic ballasts

3.6.3.1 Supply voltage and current waveforms

Figure 75 shows a typical example of the supply voltage and current waveforms recorded for the TFL test samples. The current waveform is distorted. The current waveform is symmetrical for the positive and negative halves of the supply voltage waveform, thus no even harmonic components are expected.

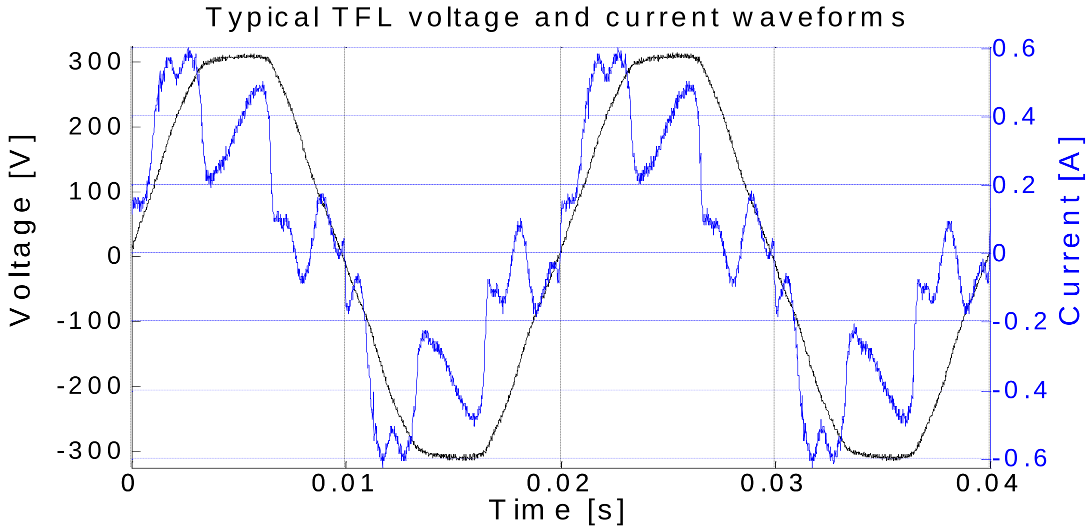

Figure 75: Typical supply voltage and current waveforms for a TFL with a magnetic ballast.

3.6.3.2 Harmonic content of the supply current

Figure 76 to Figure 79 shows the harmonic spectrum of the current waveform for the TFL sample 1 of each of the manufacturers considered in this chapter.

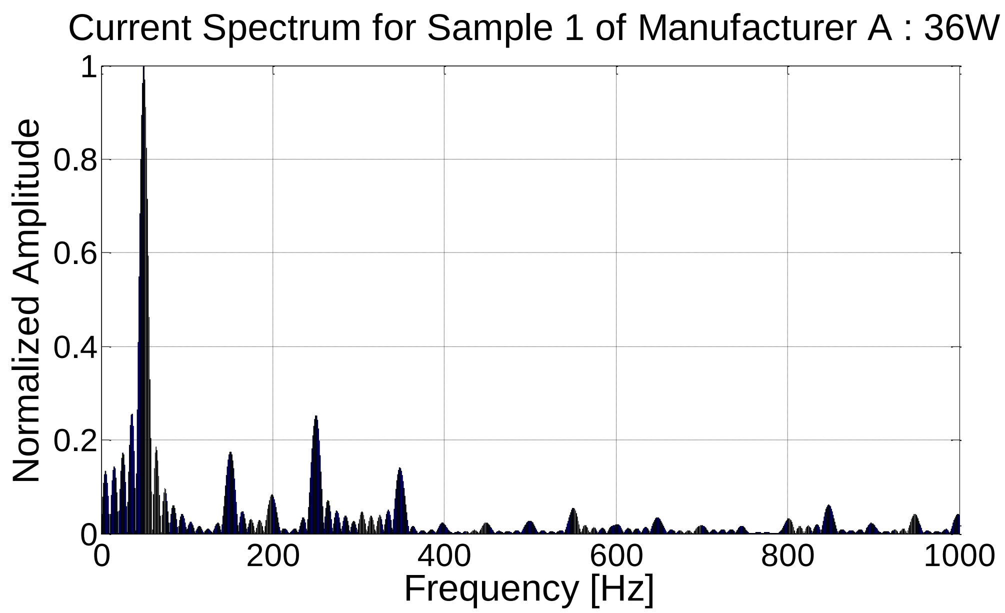

Figure 76: Current spectrum for the first 36W TFL sample from manufacturer A and magnetic ballast alpha.

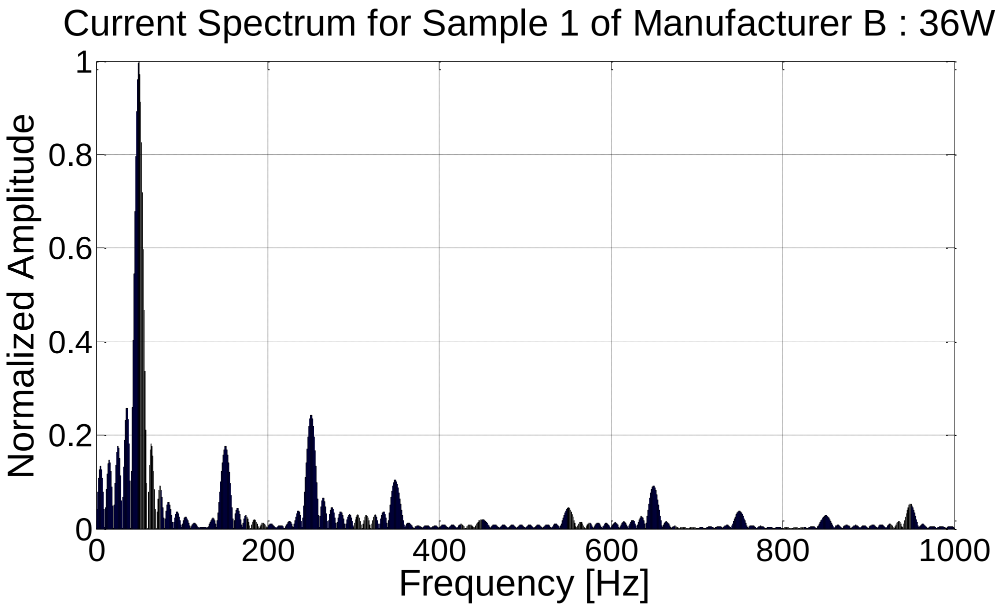

Figure 77: Current spectrum for the first 36W TFL sample from manufacturer B and magnetic ballast alpha.

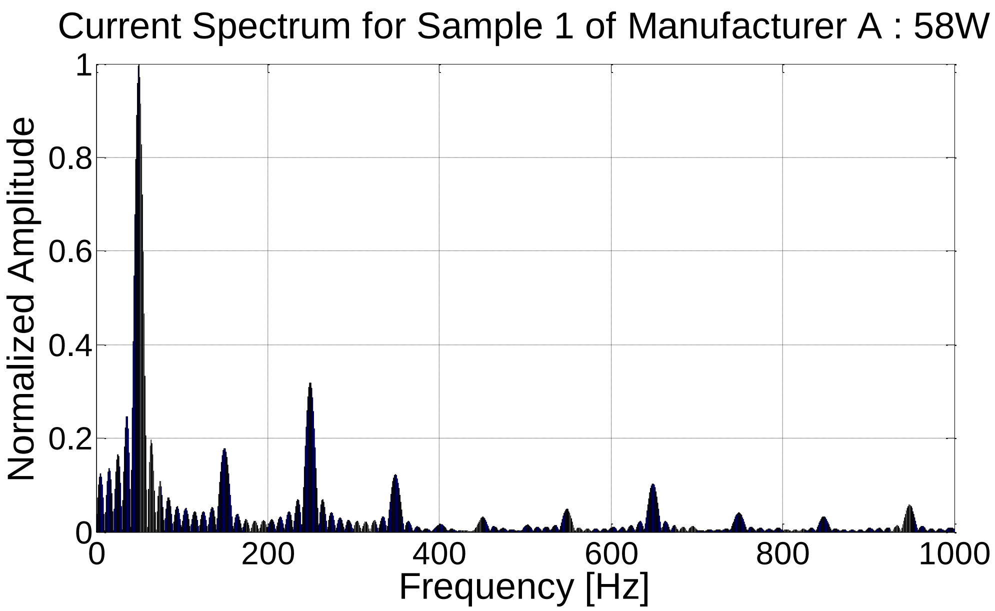

Figure 78: Current spectrum for the first 58W TFL sample from manufacturer A and magnetic ballast alpha.

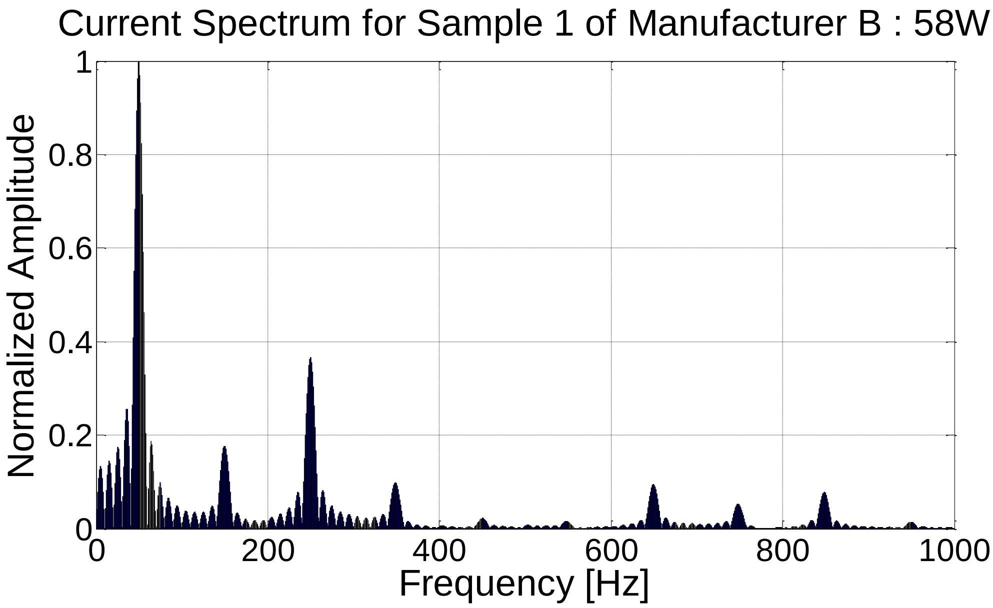

Figure 79: Current spectrum for the first 58W TFL sample from manufacturer B and magnetic ballast alpha.

Table 13 illustrates the magnitude of the third harmonic relative to the fundamental for each of the tested TFLs.

Table 13: Magnitudes of the 3rd harmonics, of the TFLs considered in this chapter, for a supply voltage of 230V.

Manufacturer / Model	Ballast type	Ballast manufacturer	Power Rating [W]	Sample number	3rd Harmonic [%]
A	Magnetic	alpha	36	1	17.514
				2	17.86
				3	18.145
			58	1	17.78
				2	18.121
				3	17.616
B	Magnetic	alpha	36	1	17.533
				2	18.855
				3	19.008
			58	1	16.216
				2	17.636
				3	16.633

Figure 80 to Figure 83 show the THD of the supply current waveforms respectively as a function of the RMS supply voltage for various TFL samples tested.

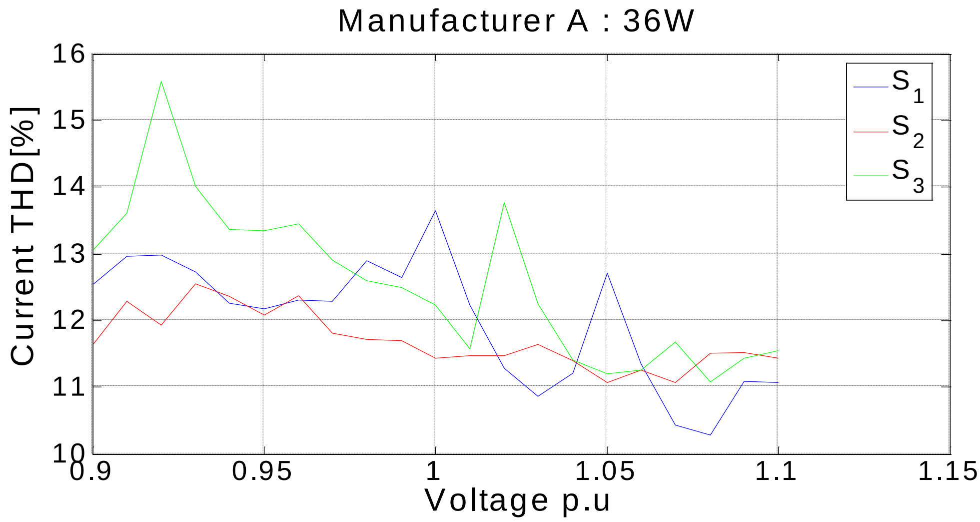

Figure 80: THD of the current waveform versus RMS supply voltage for 36W TFLs from manufacturer A and magnetic ballast alpha.

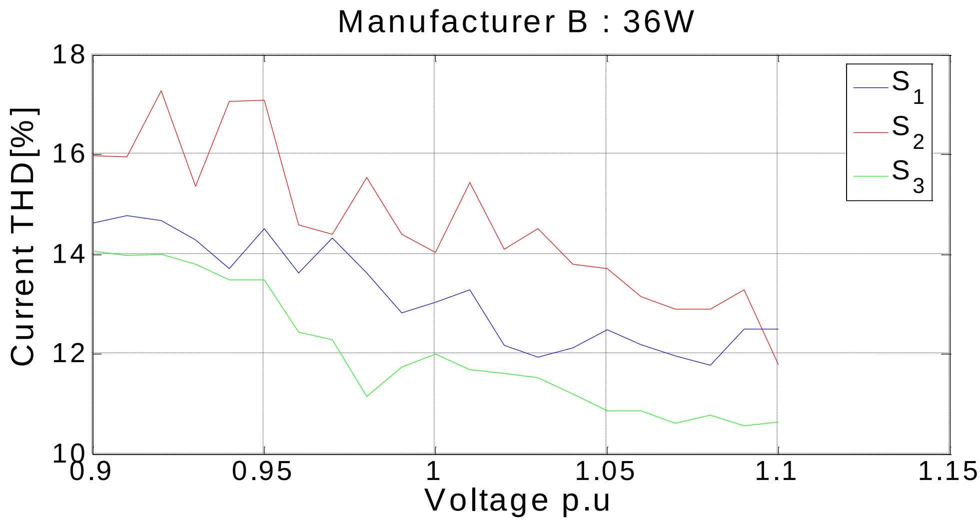

Figure 81: THD of the current waveform versus RMS supply voltage for 36W TFLs from manufacturer B and magnetic ballast alpha.

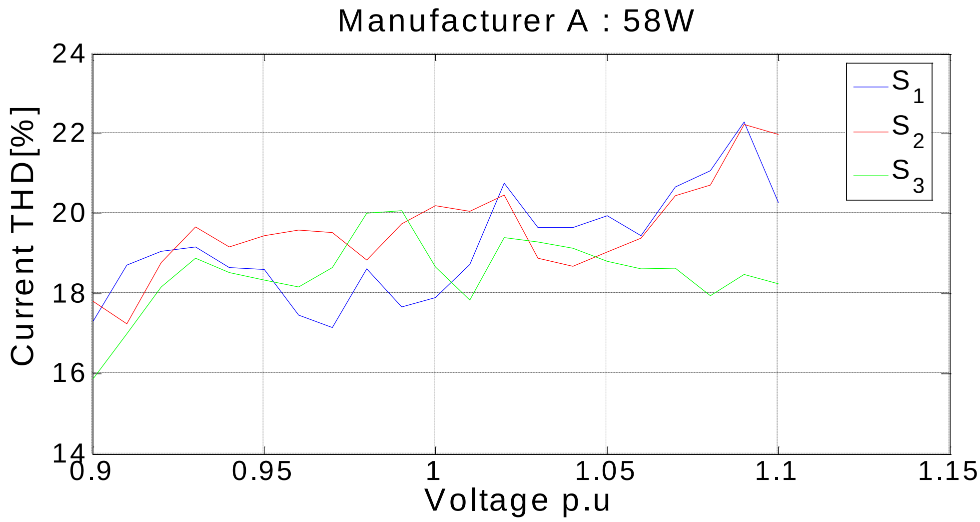

Figure 82: THD of the current waveform versus RMS supply voltage for 58W TFLs from manufacturer A and magnetic ballast alpha.

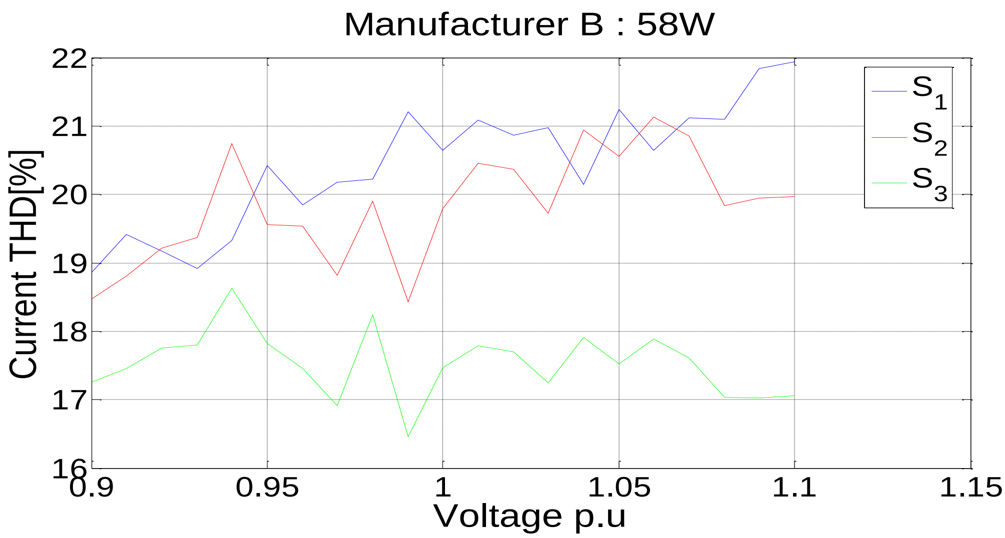

Figure 83: THD of the current waveform versus RMS supply voltage for 58W TFLs from manufacturer B and magnetic ballast alpha.

3.6.4 Zero sequence currents for TFLs with magnetic ballasts

3.6.4.1 Measurement results

Figure 84 to Figure 91 show the results for the three-phase supply current and neutral current waveforms respectively, at a supply voltage of 230V, for the TFLs considered in this chapter. The three-phase supply current yields a minimal neutral current component.

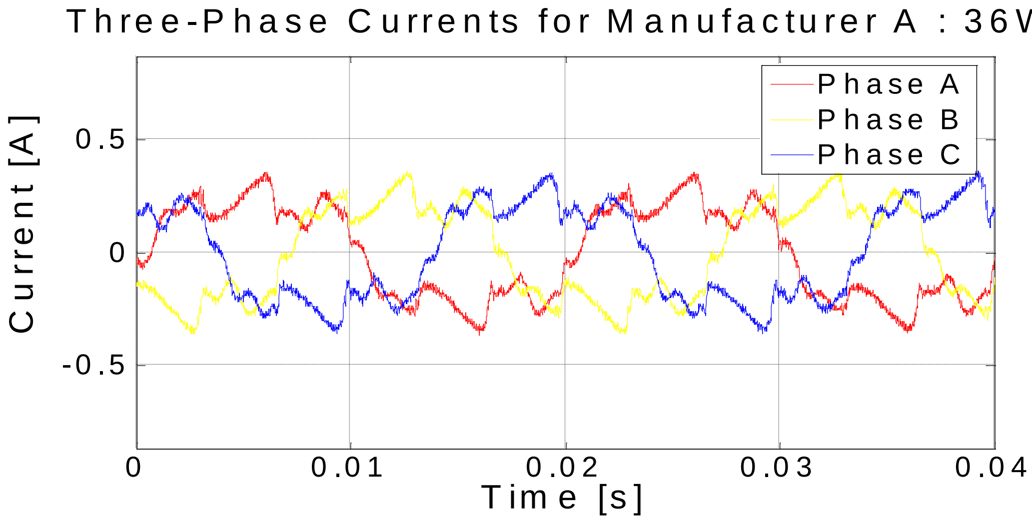

Figure 84: Three-phase current waveforms for the 36W TFLs from manufacturer A and magnetic ballast alpha.

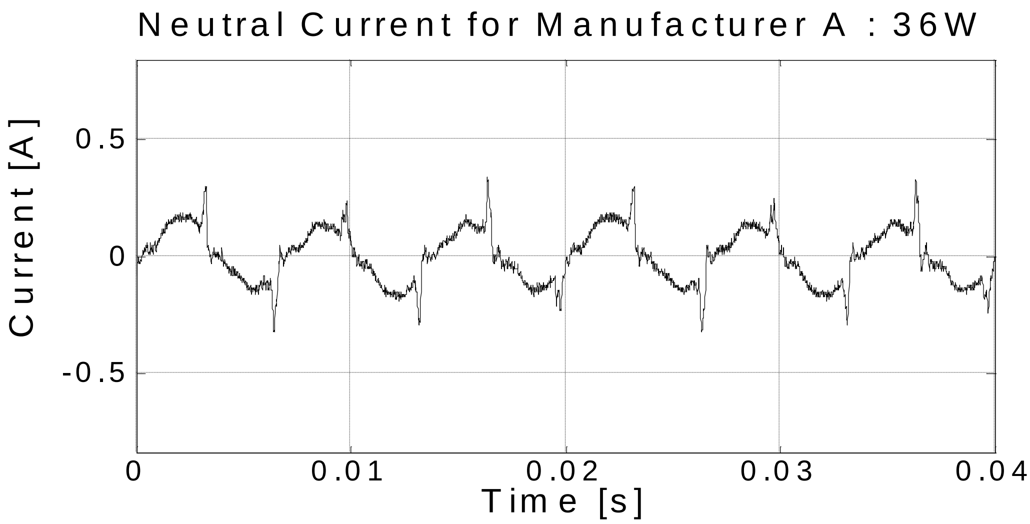

Figure 85: Neutral current waveform for the 36W TFLs from manufacturer A and magnetic ballast alpha.

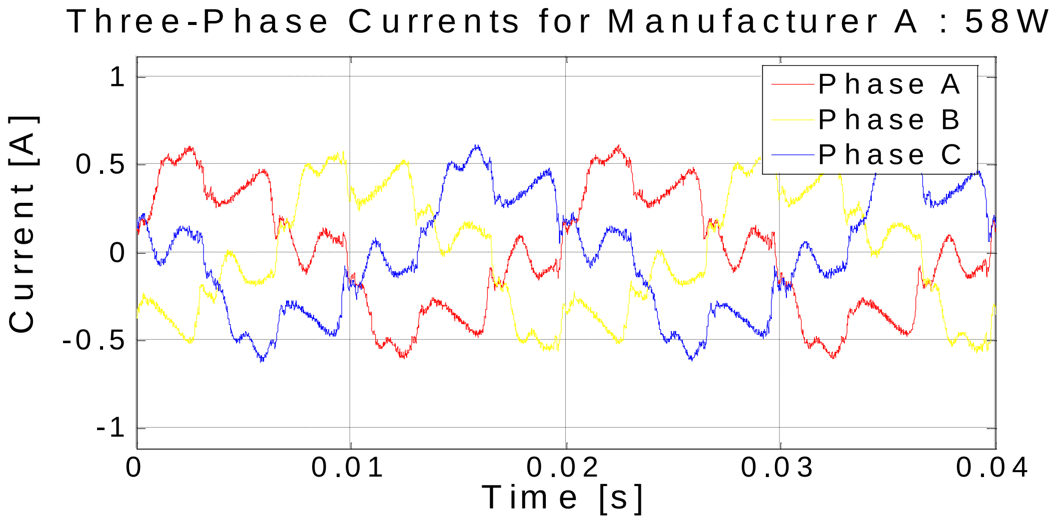

Figure 86: Three-phase current waveforms for the 58W TFLs from manufacturer A and magnetic ballast alpha.

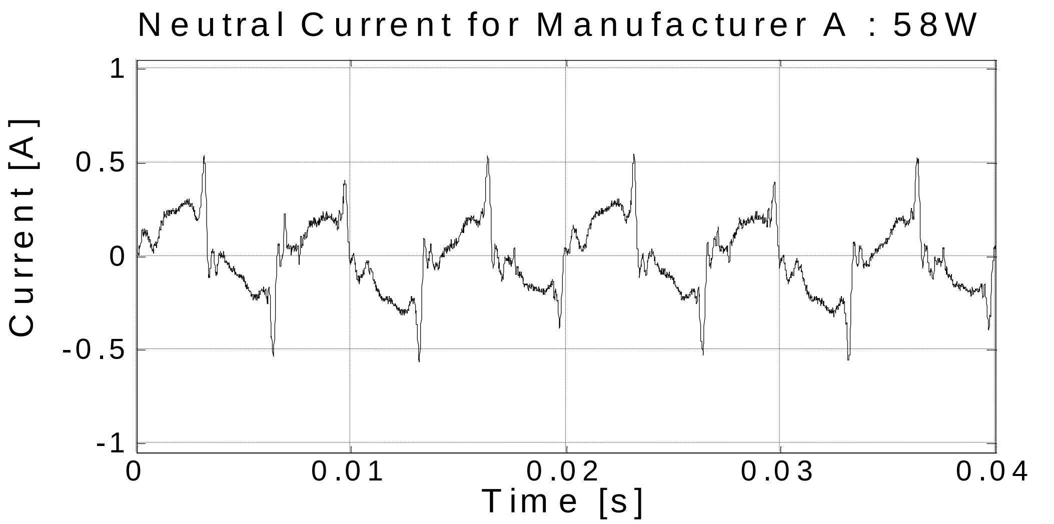

Figure 87: Neutral current waveform for the 58W TFLs from manufacturer A and magnetic ballast alpha.

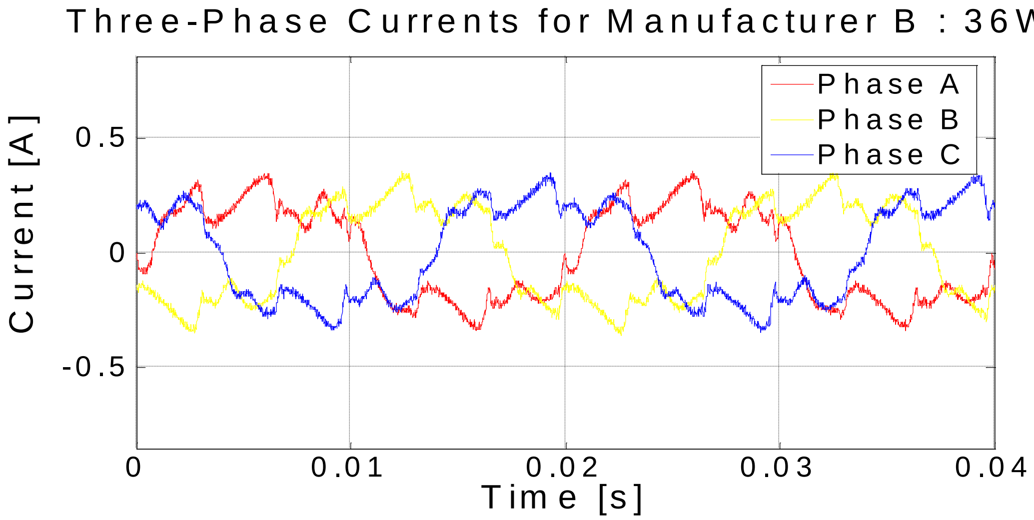

Figure 88: Three-phase current waveforms for the 36W TFLs from manufacturer B and magnetic ballast alpha.

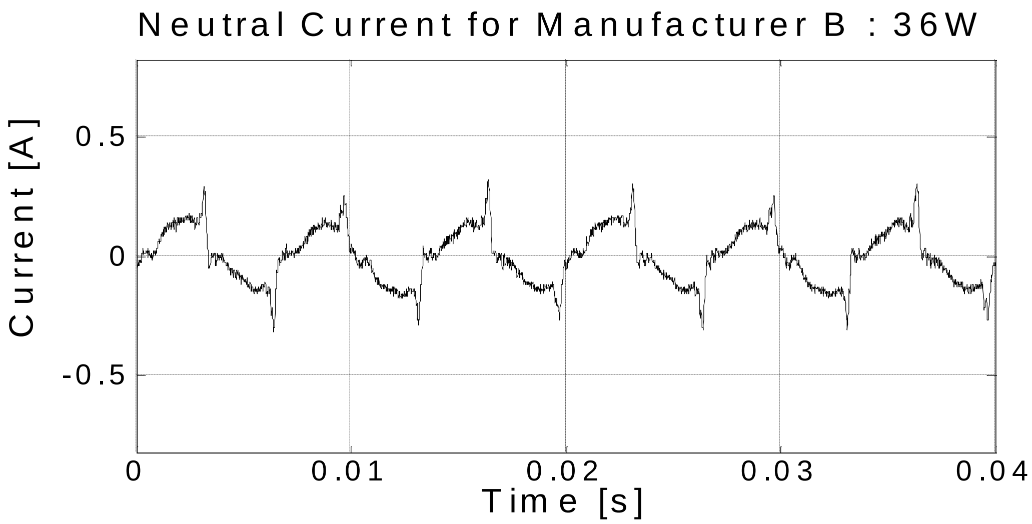

Figure 89: Neutral current waveform for the 36W TFLs from manufacturer B and magnetic ballast alpha.

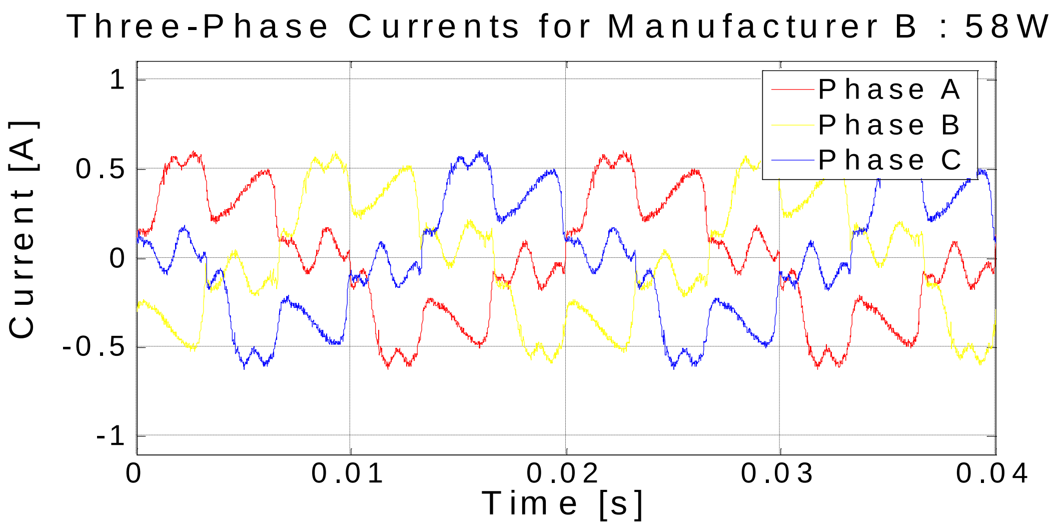

Figure 90: Three-phase current waveforms for the 58W TFLs from manufacturer B and magnetic ballast alpha.

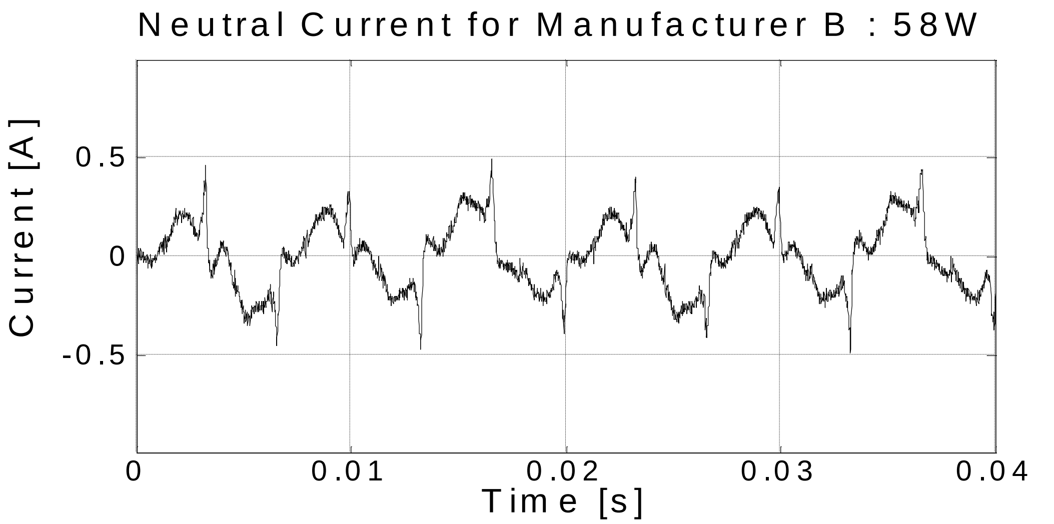

Figure 91: Neutral current waveform for the 58W TFLs from manufacturer B and magnetic ballast alpha.

Figure 92 to Figure 95 show the results for the three-phase supply current and neutral current waveforms respectively for 36W and 58W TFLs where the manufacturers are mixed.

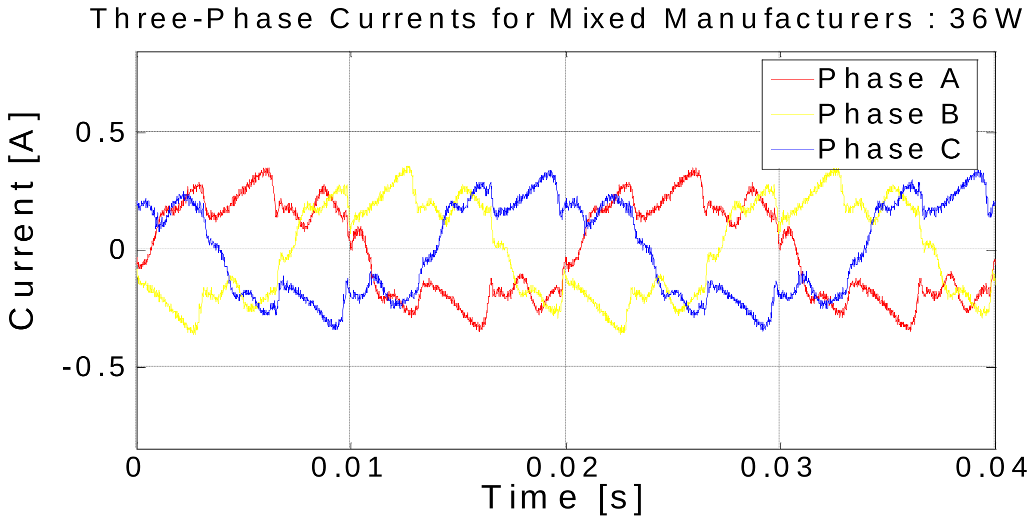

Figure 92: Three-phase current waveforms for the 36W TFLs from mixed manufacturers and magnetic ballast alpha.

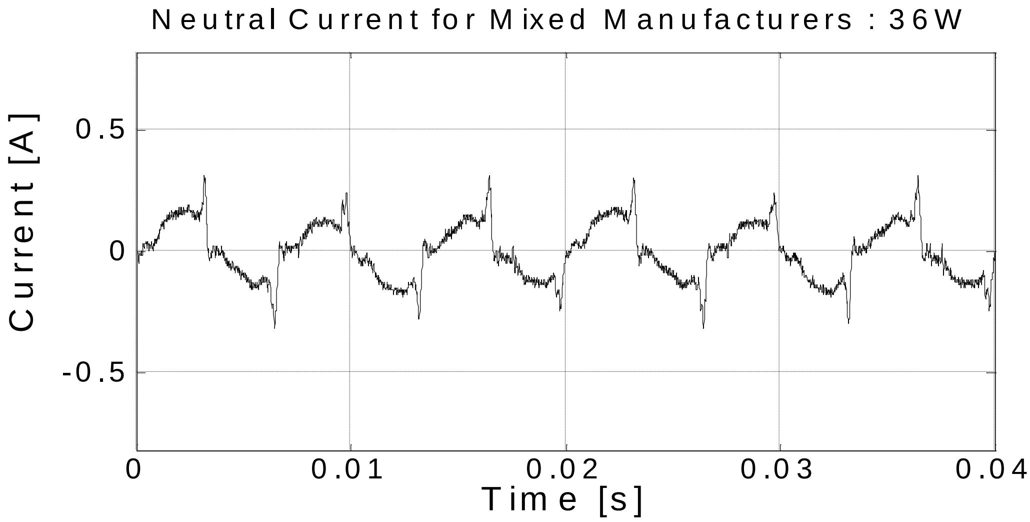

Figure 93: Neutral current waveform for the 36W TFLs from mixed manufacturers and magnetic ballast alpha.

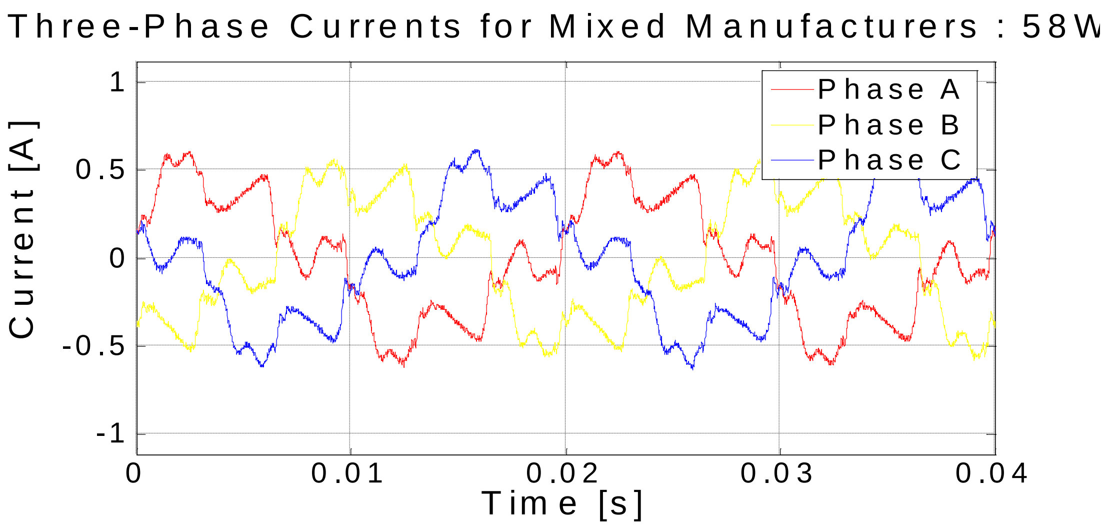

Figure 94: Three-phase current waveforms for the 58W TFLs from mixed manufacturers and magnetic ballast alpha.

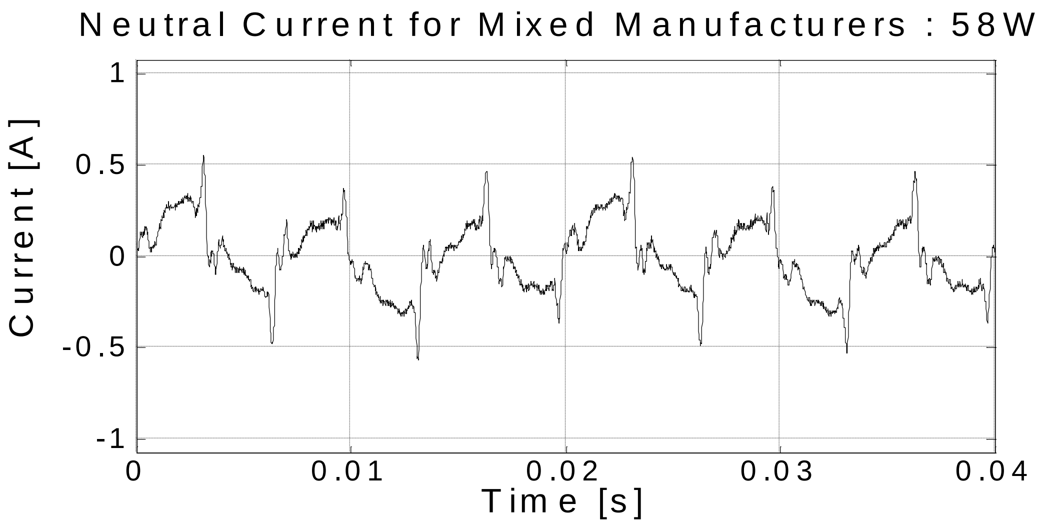

Figure 95 : Neutral current waveform for the 58W TFLs from mixed manufacturers and magnetic ballast alpha.

Table 14 contains a comparison between the phase currents and the neutral currents of the TFLs considered in this chapter.

Table 14: RMS neutral current vs. RMS phase current for TFLs with magnetic ballasts considered in this chapter.

Manufacturer / Model	Ballast	Power Rating [W]	RMS Phase A Current [mA]	RMS Phase B Current [mA]	RMS Phase C Current [mA]	RMS Neutral Current [mA]
A	alpha	36	203.1	204.8	204.1	116.67
		58	344.2	345.6	343.1	190.17
B	alpha	36	206.2	206.7	205.3	117.030
		58	341.3	344.5	342.2	189.82
Mixed (A,B,A)	alpha	36	-	-	-	116.46

Mixed (A,B,A)	alpha	58	-	-	-	193.97

3.6.5 Voltage dependency measurement results for TFLs with electronic ballasts

Appendix A contains all the data relevant to this chapter.

3.6.5.1 Modelling of the voltage dependency of the active power consumption of TFLs with electronic ballasts

Table 15 summarizes the polynomial curve fitting models determined for each of the TFL types evaluated.

Table 15: TFL power consumption models the individual curve derived.

Manufacturer / Model	Ballast type	Ballast manufacturer	Power Rating [W]	Active power model [W]
A	Electronic	alpha	36	$0.12614V + 7.7155$
			58	$0.24593V - 2.1523$
B	Electronic	alpha	36	$0.17357V - 4.1538$
			58	$0.23329V - 0.66079$

Figure 96 to Figure 99 compare the active power versus RMS supply voltage responses of the models (M) to the original measurements obtained for each TFL sample. The correlations of the measurements between the different models are generally good. The results for the samples of the same rating from the same manufacturer vary from almost identical to a spread of approximately 9% as for the 36W units from manufacturer A for example.

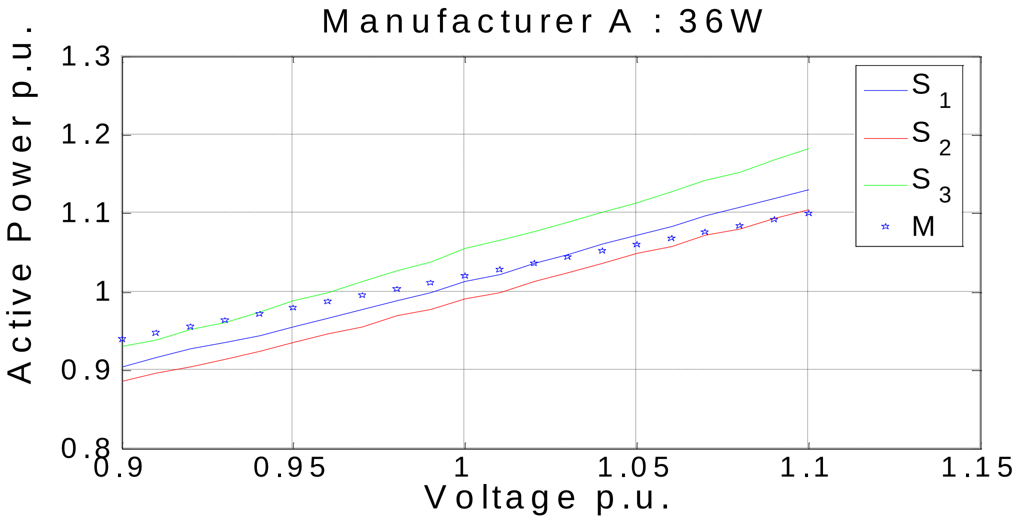

Figure 96: Measured and modelled active power consumption versus RMS supply voltage for the 36 W TFL samples from manufacturer A and electronic ballast alpha.

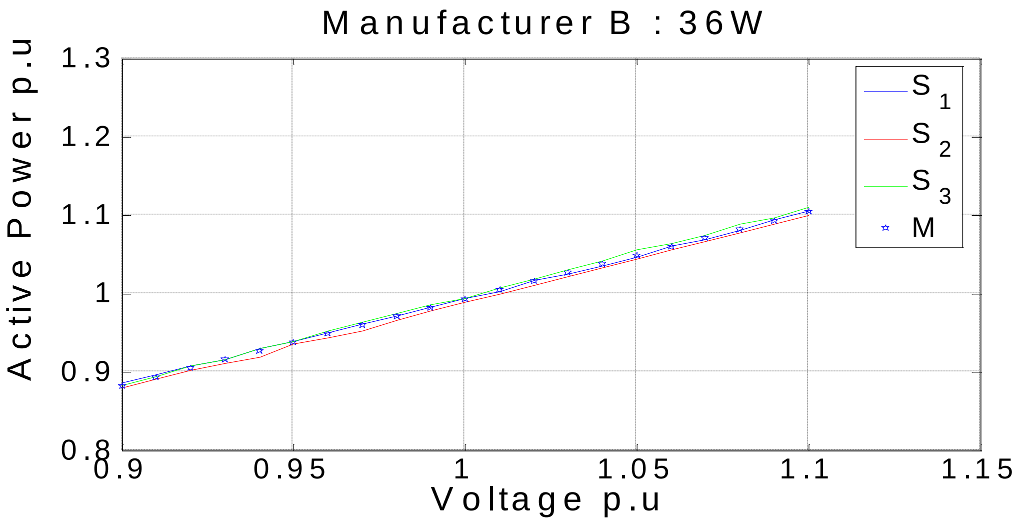

Figure 97: Measured and modelled active power consumption versus RMS supply voltage for the 36 W TFL samples from manufacturer B and electronic ballast alpha.

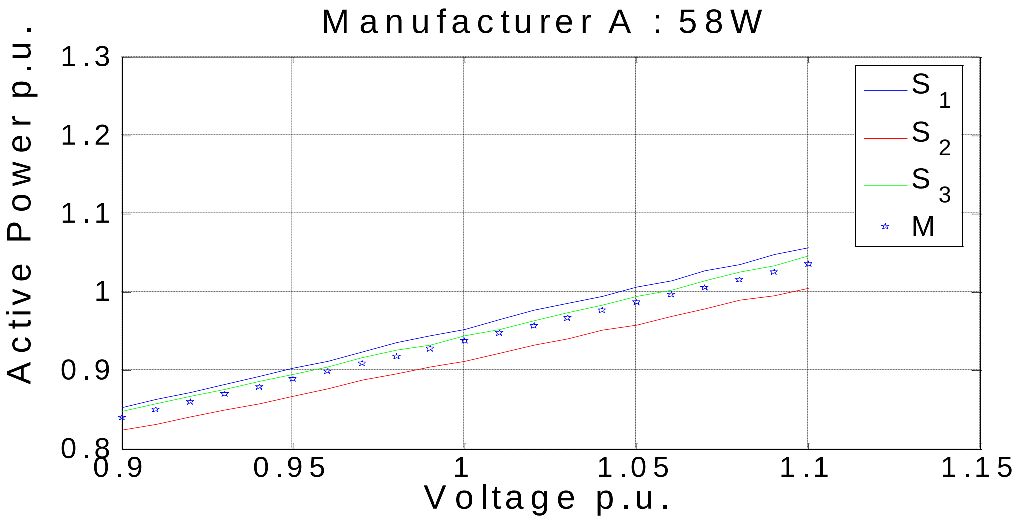

Figure 98: Measured and modelled active power consumption versus RMS supply voltage for the 58 W TFL samples from manufacturer A and electronic ballast alpha.

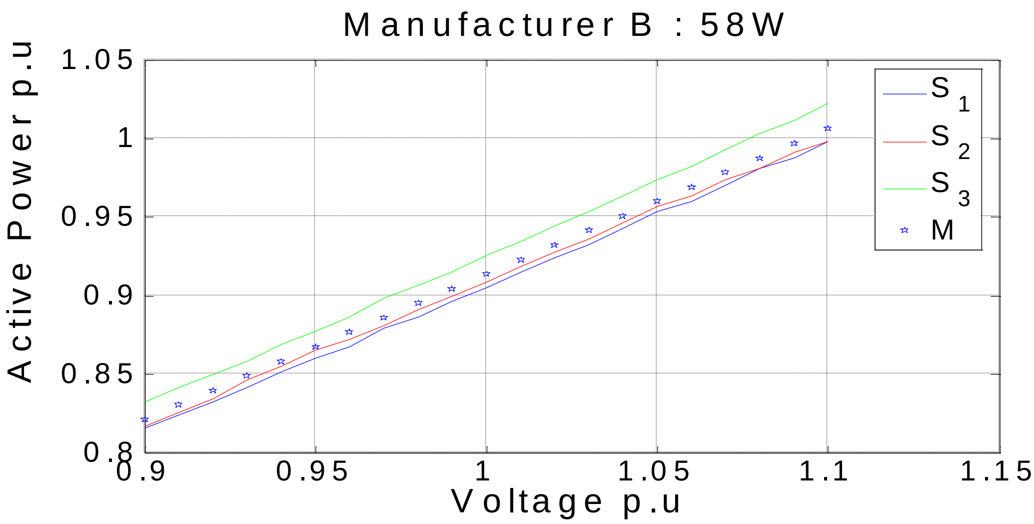

Figure 99: Measured and modelled active power consumption versus RMS supply voltage for the 58 W TFL samples from manufacturer B and electronic ballast alpha.

3.6.6 Waveform and spectral analysis for TFLs with electronic ballasts

3.6.6.1 Supply voltage and current waveforms

Figure 100 shows a typical example of the supply voltage and current waveforms recorded for the TFL test samples. The current waveform appears distorted. The current waveform is symmetrical for the positive and negative halves of the supply voltage waveform, thus no even harmonic components are expected.

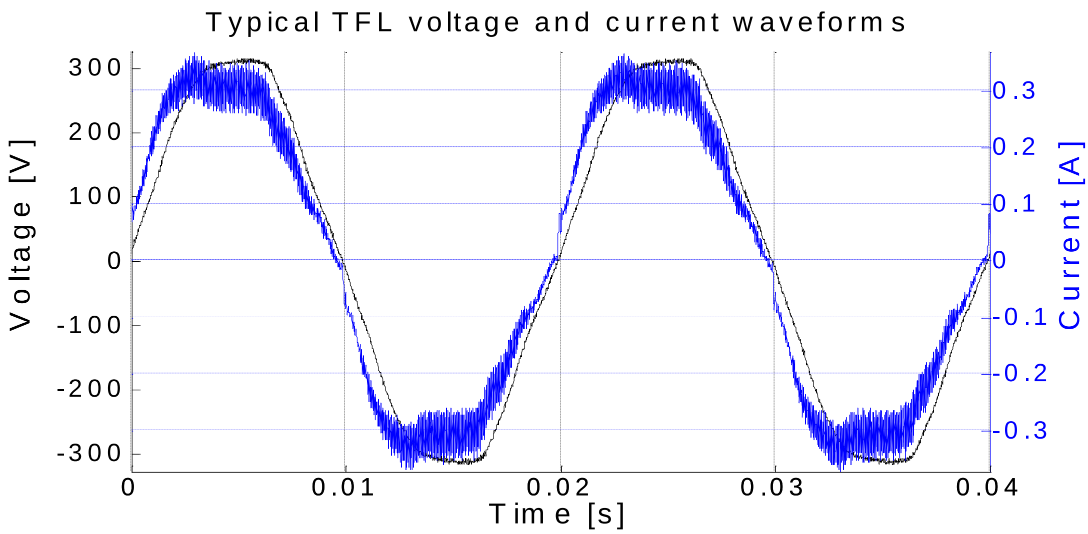

Figure 100: Typical supply voltage and current waveforms for a TFL with an electronic ballast.

3.6.6.2 Harmonic content of the supply current

Figure 101 to Figure 104 shows the harmonic spectrum of the current waveform for the TFL sample 1 of each of the manufacturers considered in this chapter. The current spectrums exhibit a moderate to low amount of uneven harmonics.

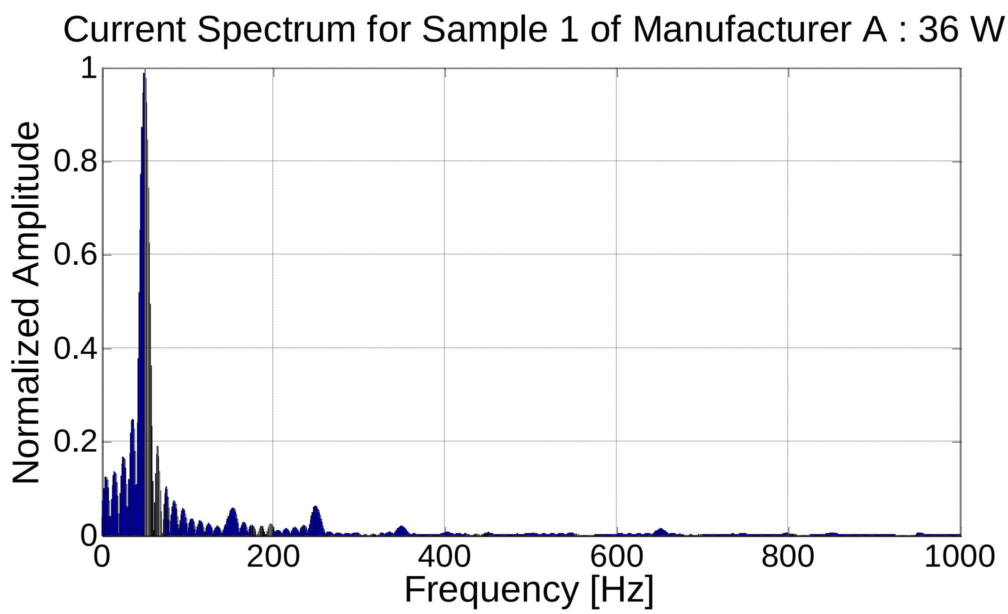

Figure 101: Current spectrum for the first 36W TFL sample from manufacturer A and electronic ballast alpha.

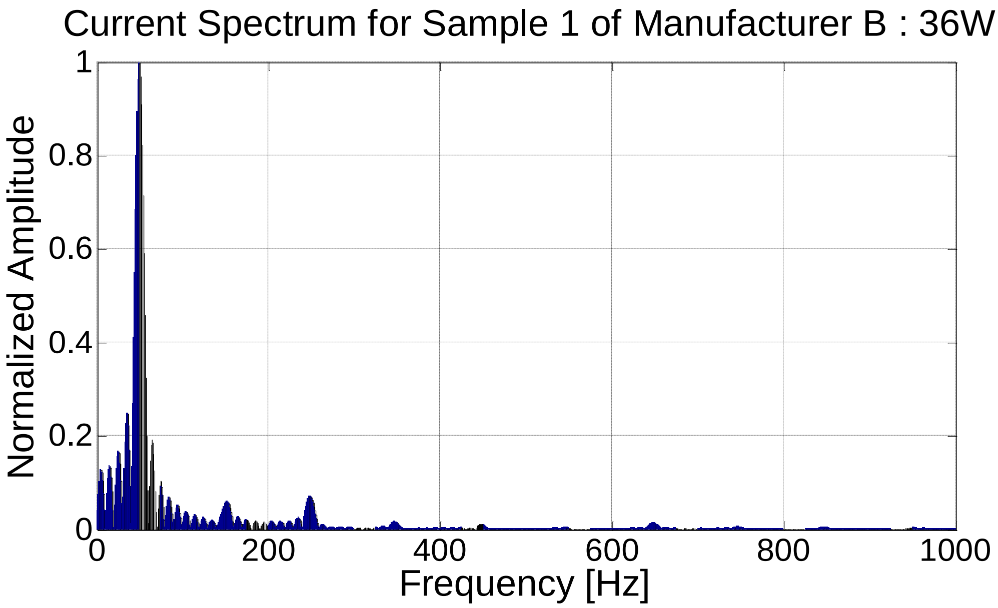

Figure 102: Current spectrum for the first 36W TFL sample from manufacturer B and electronic ballast alpha.

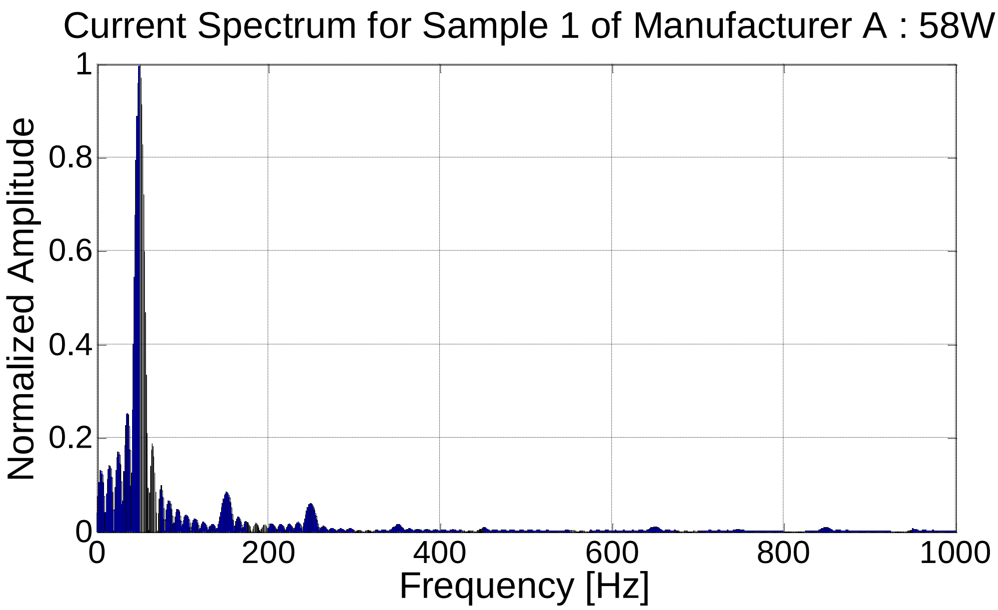

Figure 103: Current spectrum for the first 58W TFL sample from manufacturer A and electronic ballast alpha.

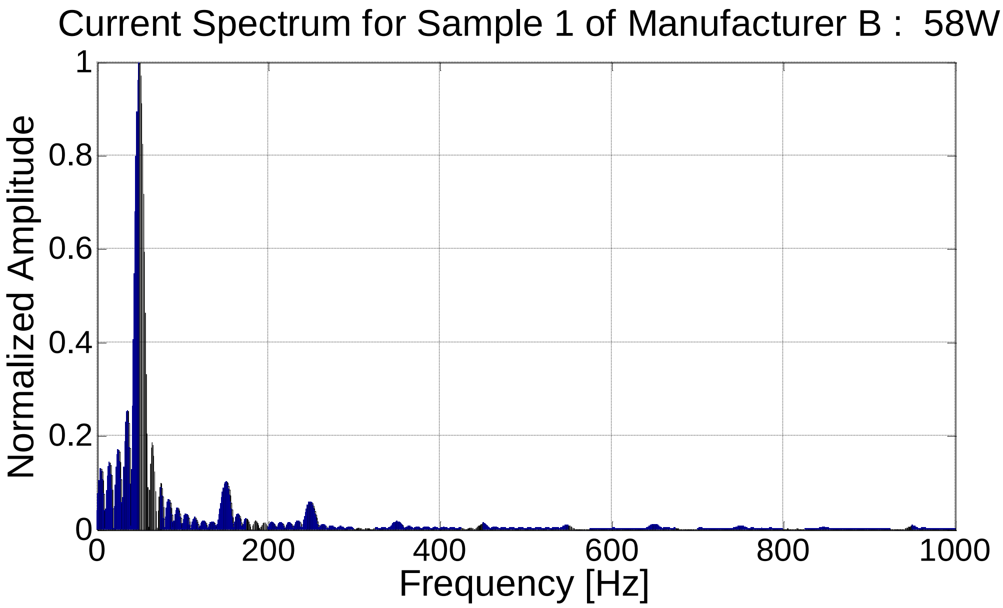

Figure 104: Current spectrum for the first 58W TFL sample from manufacturer B and electronic ballast alpha.

Table 16 illustrates the magnitude of the third harmonic relative to the fundamental for each of the tested TFLs.

Table 16: Magnitudes of the 3rd harmonics, of the TFLs considered in this chapter, for a supply voltage of 230V.

Manufacturer / Model	Ballast type	Ballast manufacturer	Power Rating [W]	Sample number	3rd Harmonic [%]
A	Electronic	alpha	36	1	5.08
				2	4.18
				3	2.92
			58	1	8.12
				2	8.43
				3	8.72
B	Electronic	alpha	36	1	5.77
				2	4.45
				3	4.09
			58	1	10.07
				2	9.48
				3	9.62

Figure 105 to Figure 108 show the THD of the supply current waveforms respectively as a function of the RMS supply voltage for various TFL samples tested.

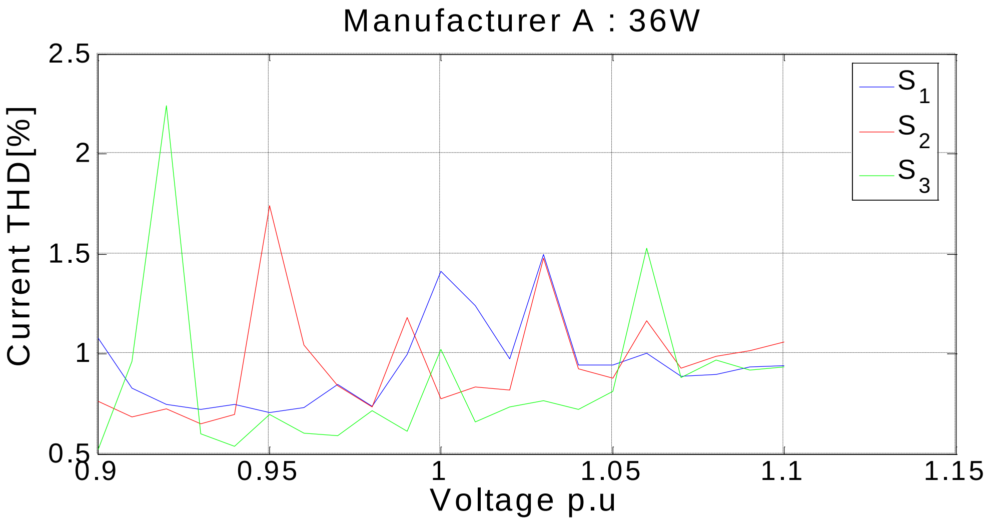

Figure 105: THD of the current waveform versus RMS supply voltage for 36W TFLs from manufacturer A and electronic ballast alpha.

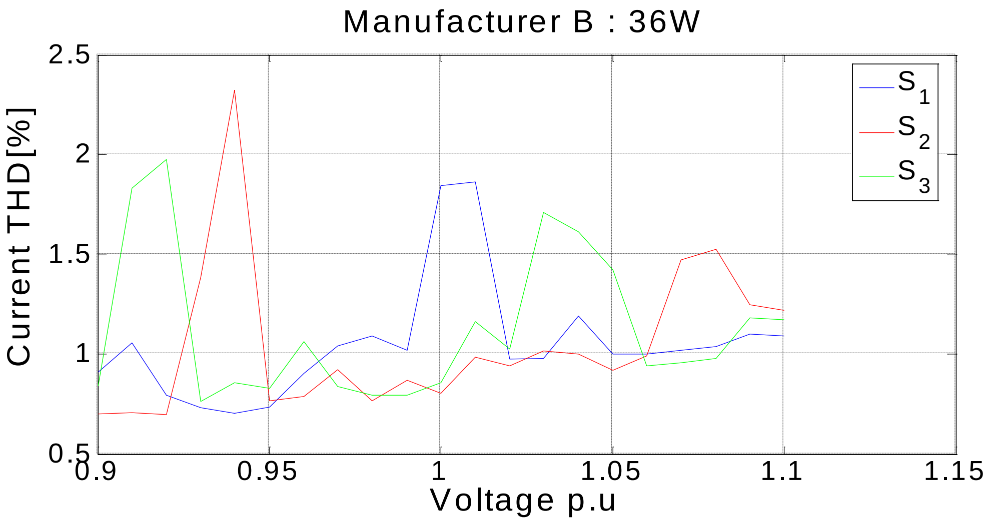

Figure 106: THD of the current waveform versus RMS supply voltage for 36W TFLs from manufacturer B and electronic ballast alpha.

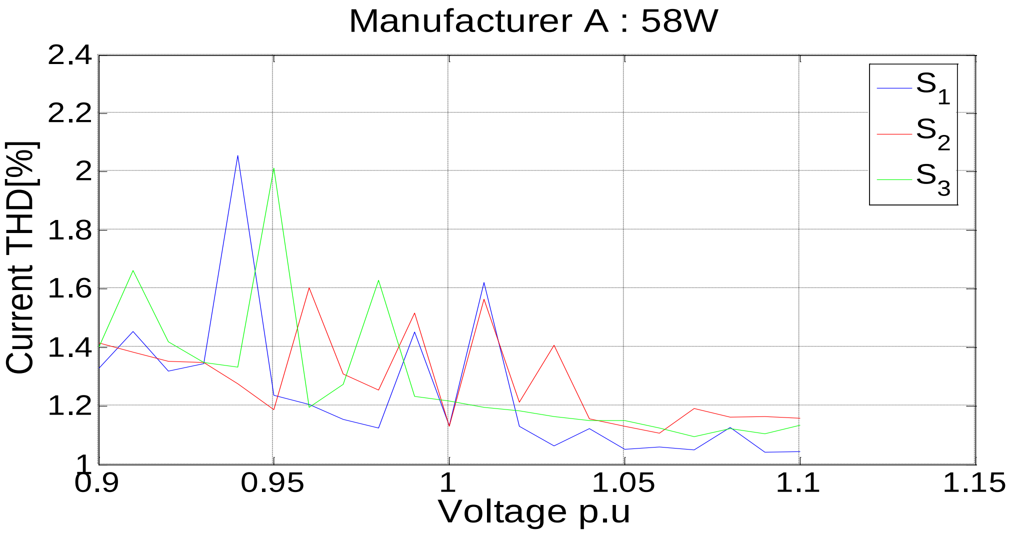

Figure 107: THD of the current waveform versus RMS supply voltage for 58W TFLs from manufacturer A and electronic ballast alpha.

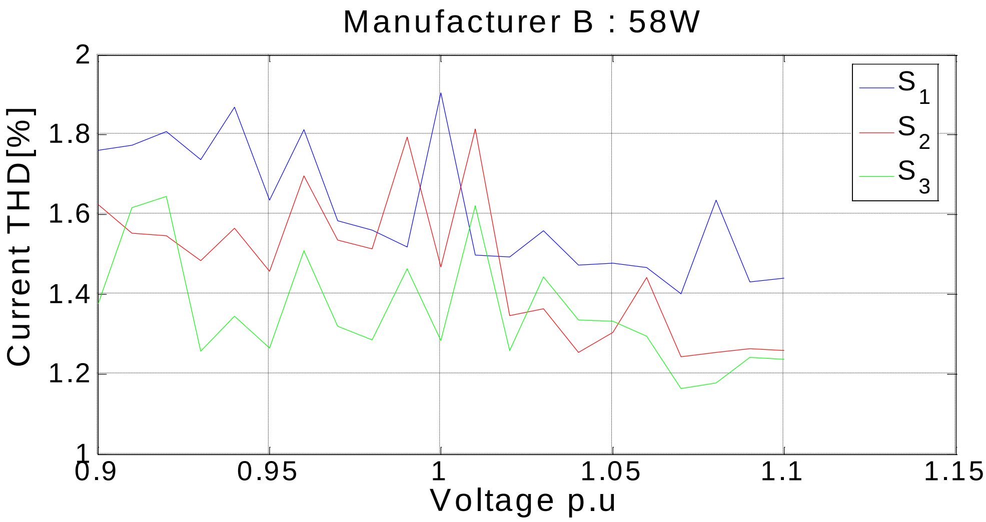

Figure 108: THD of the current waveform versus RMS supply voltage for 58W TFLs from manufacturer B and electronic ballast alpha..

3.6.7 Zero sequence currents for TFLs with electronic ballasts

3.6.7.1 Measurement results

Figure 109 to Figure 116 show the results for the three-phase supply current and neutral current waveforms respectively, at a supply voltage of 230V, for the TFLs considered in this chapter. The three-phase supply current yields a moderate neutral current component.

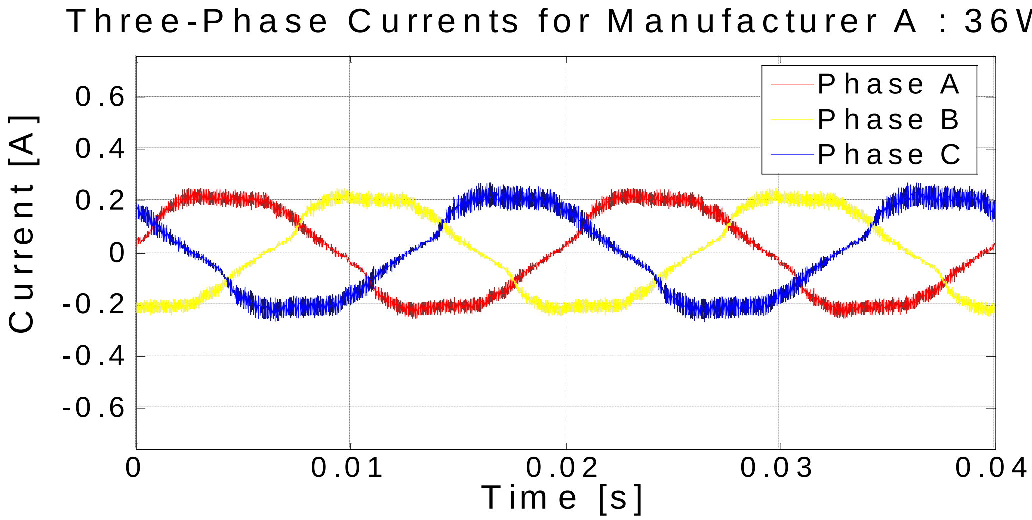

Figure 109: Three-phase current waveforms for the 36W TFLs from manufacturer A and electronic ballast alpha.

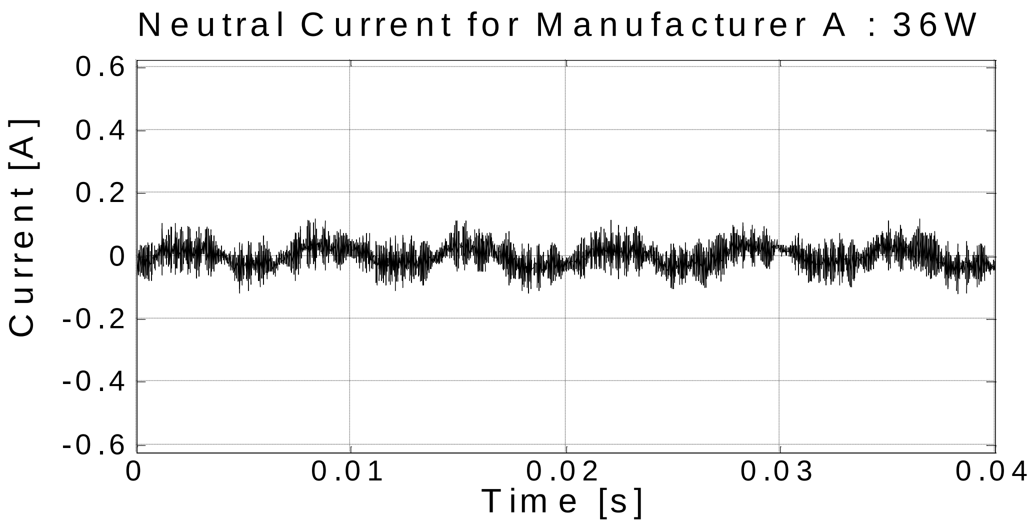

Figure 110: Neutral current waveform for the 36W TFLs from manufacturer A and electronic ballast alpha.

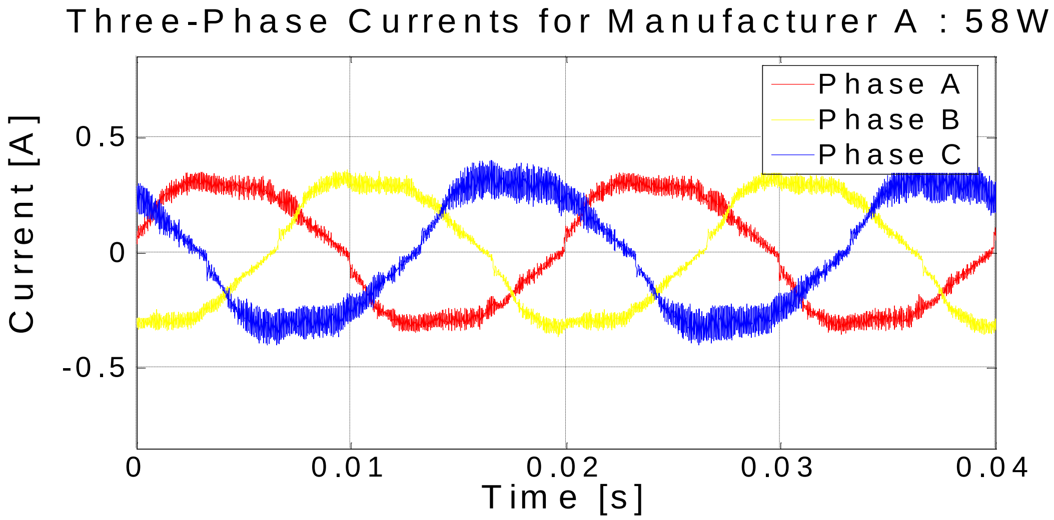

Figure 111: Three-phase current waveforms for the 58W TFLs from manufacturer A and electronic ballast alpha.

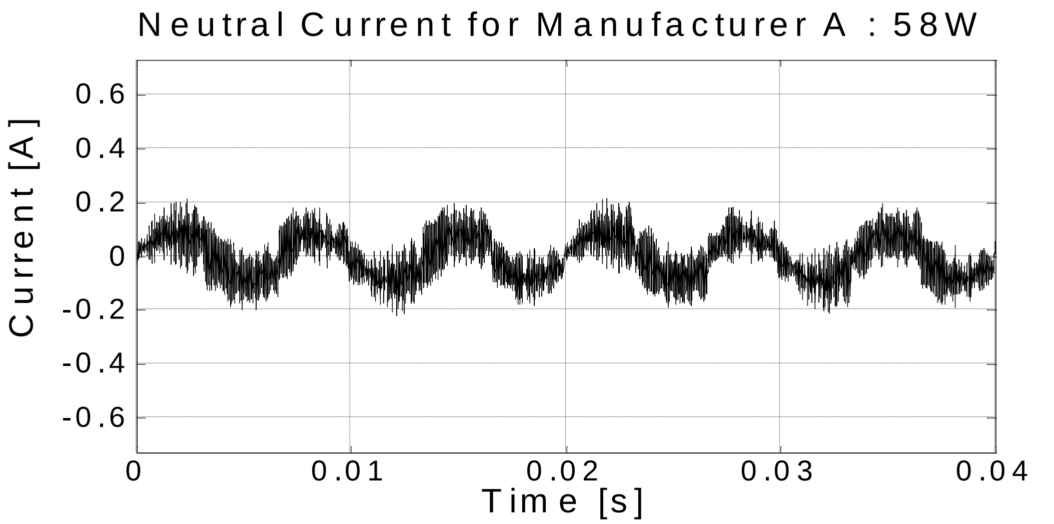

Figure 112: Neutral current waveform for the 58W TFLs from manufacturer A and electronic ballast alpha.

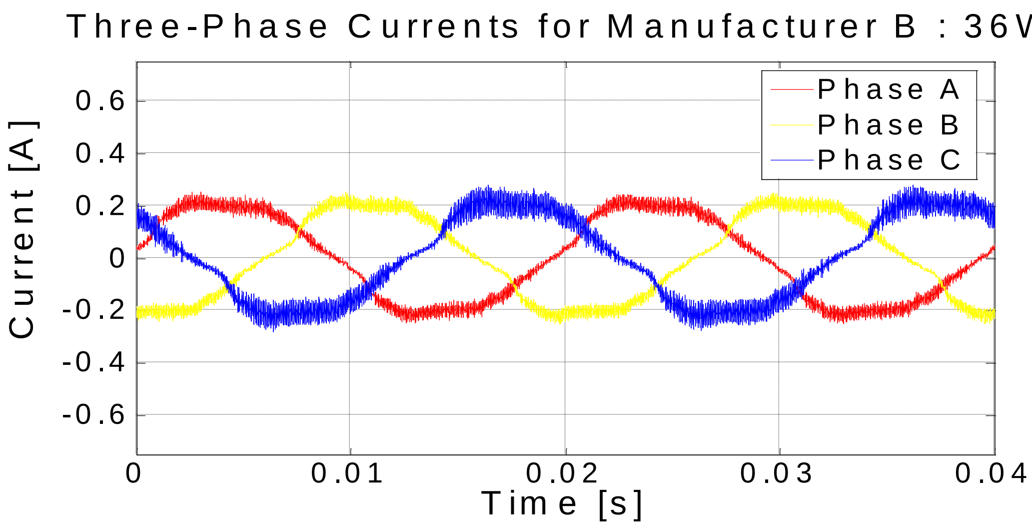

Figure 113: Three-phase current waveforms for the 36W TFLs from manufacturer B and electronic ballast alpha.

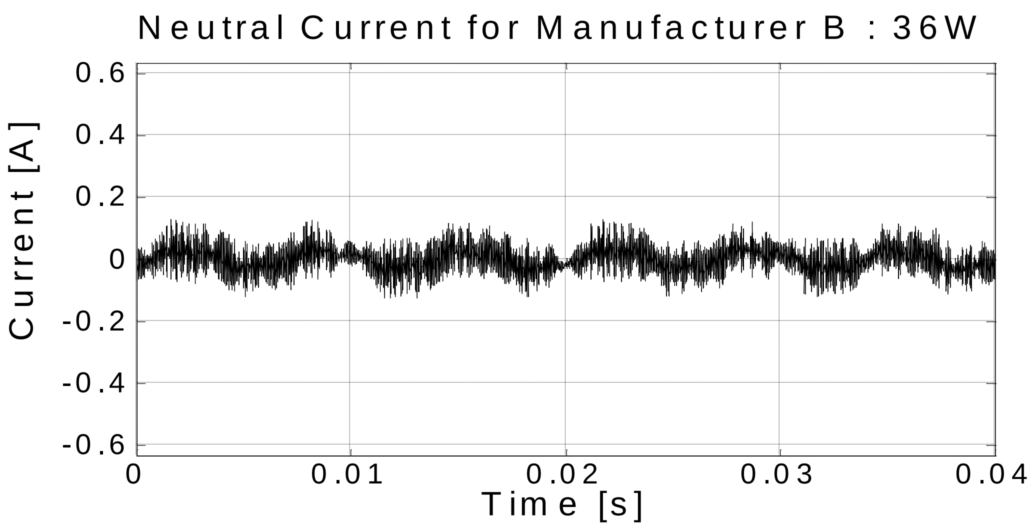

Figure 114: Neutral current waveform for the 36W TFLs from manufacturer B and electronic ballast alpha.

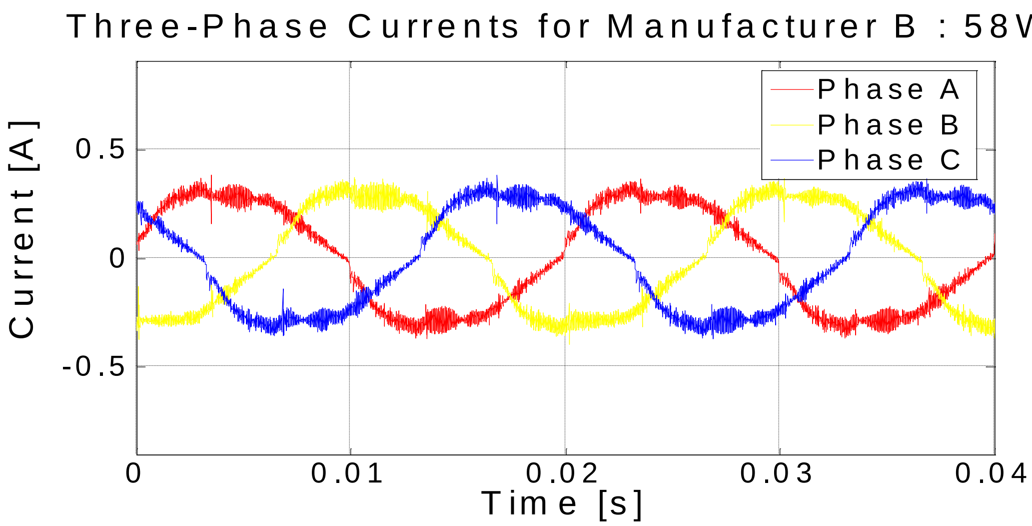

Figure 115: Three-phase current waveforms for the 58W TFLs from manufacturer B and electronic ballast alpha.

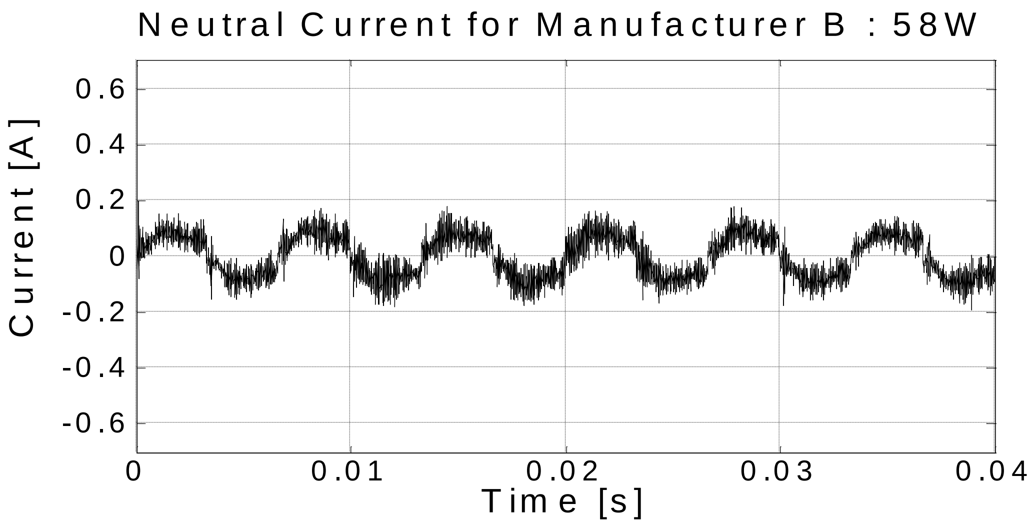

Figure 116: Neutral current waveform for the 58W TFLs from manufacturer B and electronic ballast alpha.

Figure 117 to Figure 120 show the results for the three-phase supply current and neutral current waveforms respectively for 36W and 58W TFLs where the manufacturers are mixed.

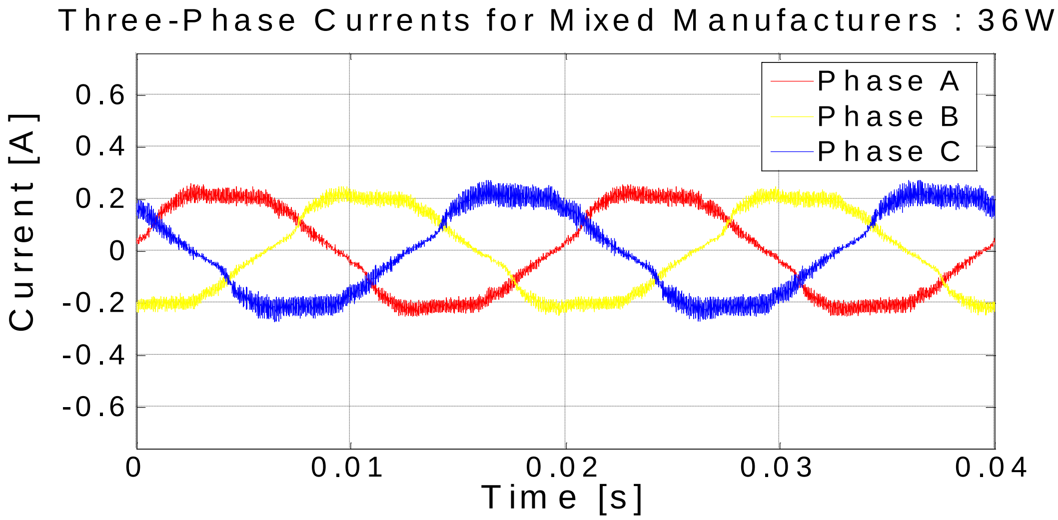

Figure 117: Three-phase current waveforms for the 36W TFLs from mixed manufacturers and electronic ballast alpha.

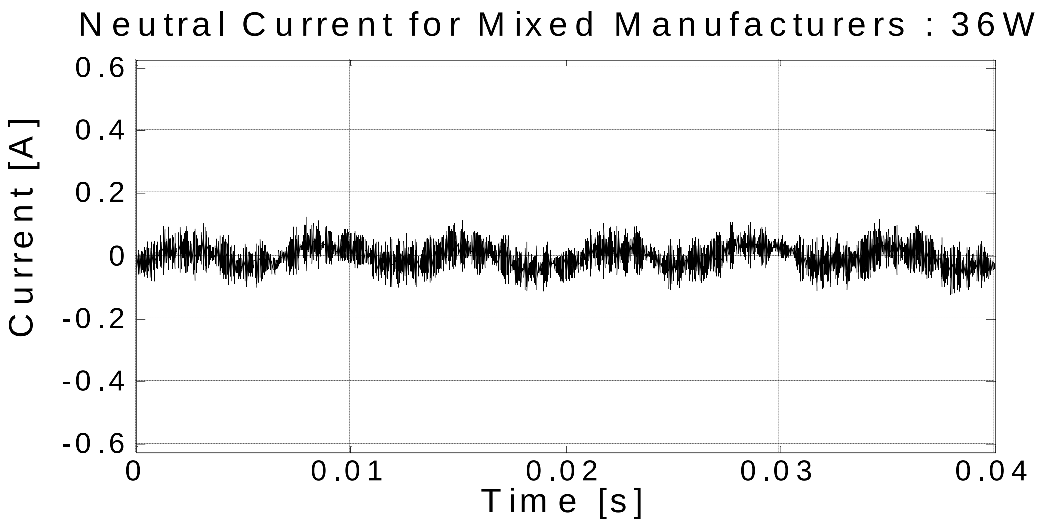

Figure 118: Neutral current waveform for the 36W TFLs from mixed manufacturers and electronic ballast alpha.

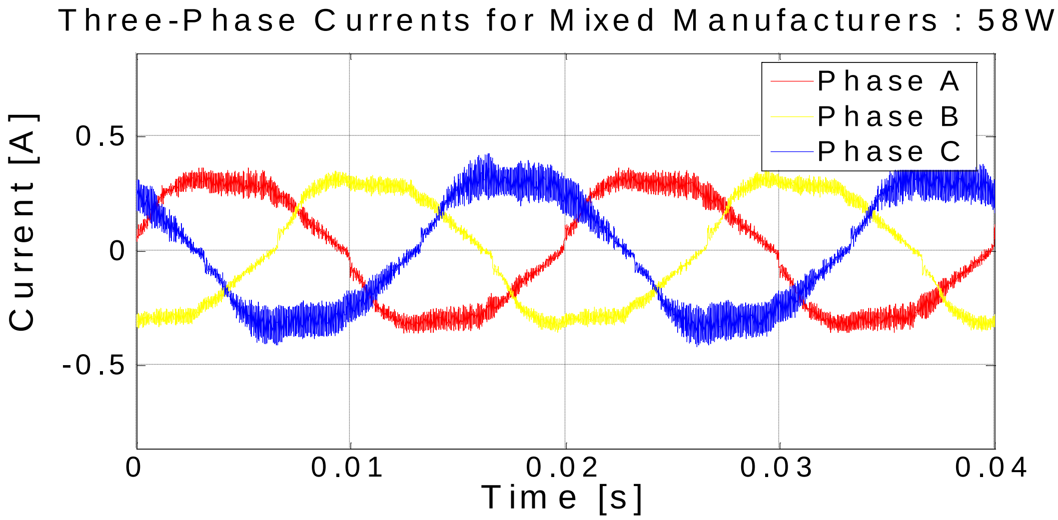

Figure 119: Three-phase current waveforms for the 58W TFLs from mixed manufacturers and electronic ballast alpha.

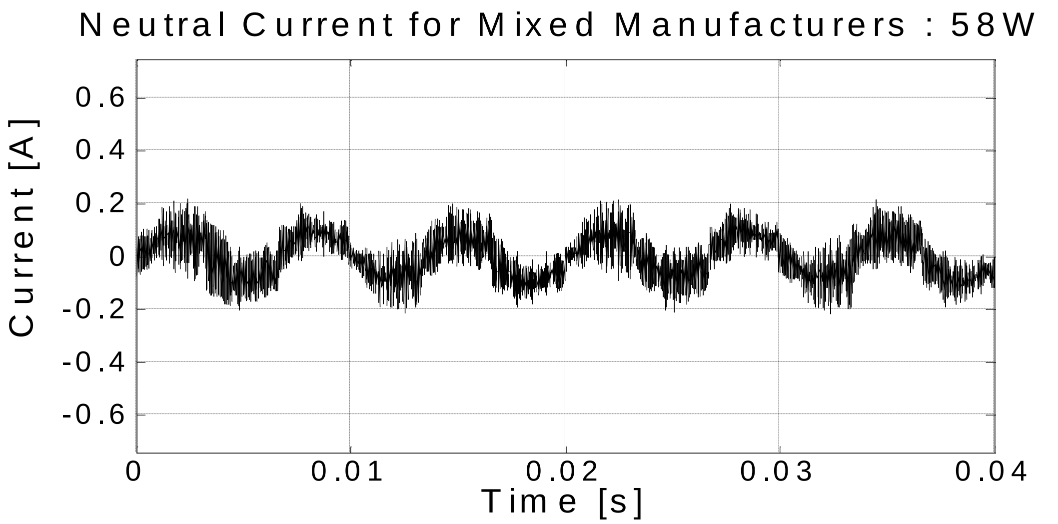

Figure 120 : Neutral current waveform for the 58W TFLs from mixed manufacturers and electronic ballast alpha.

Table 17 contains a comparison between the phase currents and the neutral currents of the TFLs considered in this chapter.

Table 17: RMS neutral current vs. RMS phase current for TFLs with an electronic ballast considered in this chapter.

Manufacturer / Model	Ballast	Power Rating [W]	RMS Phase A Current [mA]	RMS Phase B Current [mA]	RMS Phase C Current [mA]	RMS Neutral Current [mA]
A	Alpha	36	162.6	159	168.8	41.43333
		58	246.8	236.8	244.1	86.26667
B	Alpha	36	160.1	158.5	159.8	46.73333
		58	235.4	236.3	239.8	84.77

Mixed (A,B,A)	Alpha	36	-	-	-	42.2
Mixed (A,B,A)	Alpha	58	-	-	-	87.73

3.7 Results for high intensity discharge lamps

3.7.1 Overview

A variety of commercial HIDLs of different ratings and from different manufacturers were tested. In order to determine whether the test results are consistent for HIDLs of the same rating from the same manufacturer, three samples of each rating per manufacturer were tested. Table 18 summarizes the subsection of the test results that are presented in this chapter.

Table 18: Summary of the HIDLs considered in this chapter

Manufacturer / Model	Magnetic ballast manufacturer	Power Rating [W]
A	alpha	400
B	alpha	400

3.7.2 Voltage dependency measurement results

Appendix A contains all the data relevant to this chapter.

3.7.2.1 Modelling of the voltage dependency of the active power consumption of HIDLs

Table 19 summarizes the polynomial curve fitting models determined for each of the HIDL types evaluated.

Table 19: HIDL power consumption models the individual curve derived.

Manufacturer / Model	Ballast type	Ballast manufacturer	Power Rating [W]	Active power model [W]
A	Magnetic	alpha	400	$3.4701V - 436.24$
B	Magnetic	alpha	400	$3.3165V - 399.92$

Figure 121 to Figure 122 compare the active power versus RMS supply voltage responses of the models (M) to the original measurements obtained for each HIDL sample. The correlations of the measurements between the different models are generally good. The results for the samples of the same rating from the same manufacturer show a spread of approximately 5%.

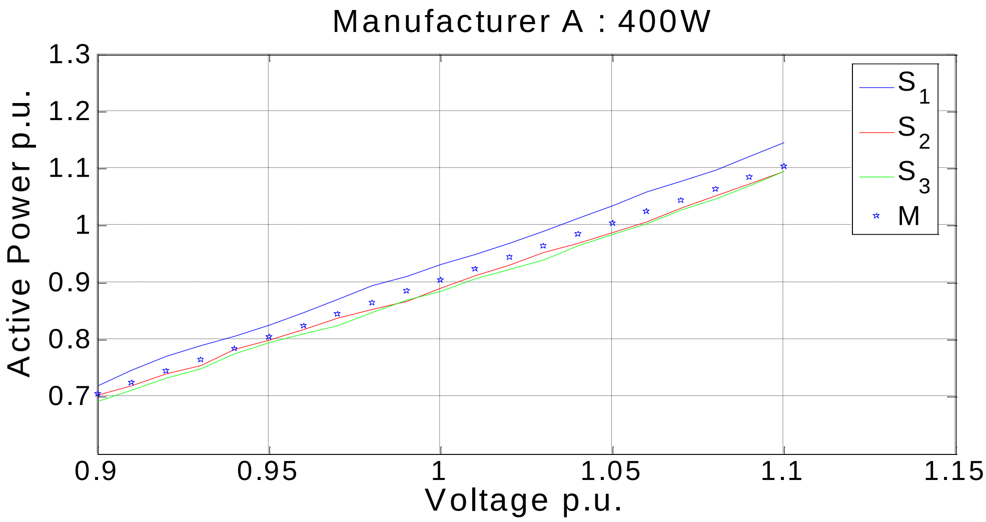

Figure 121: Measured and modelled active power consumption versus RMS supply voltage for the 400 W HIDL samples from manufacturer A and magnetic ballast alpha.

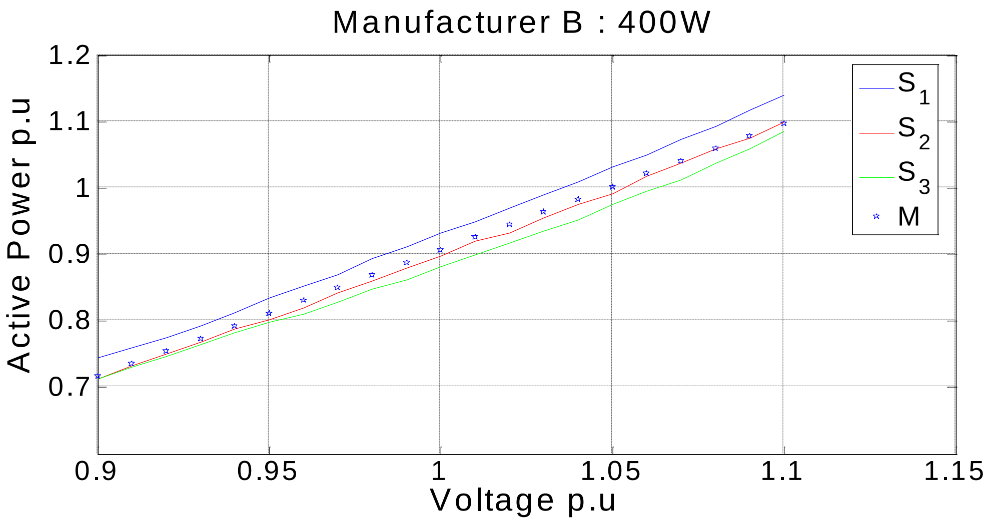

Figure 122: Measured and modelled active power consumption versus RMS supply voltage for the 400 W HIDL samples from manufacturer B and magnetic ballast alpha.

3.7.3 Waveform and spectral analysis

3.7.3.1 Supply voltage and current waveforms

Figure 123 shows a typical example of the supply voltage and current waveforms recorded for the HIDL test samples. The current waveform is moderately distorted. The current waveform is symmetrical for the positive and negative halves of the supply voltage waveform, thus no even harmonic components are expected.

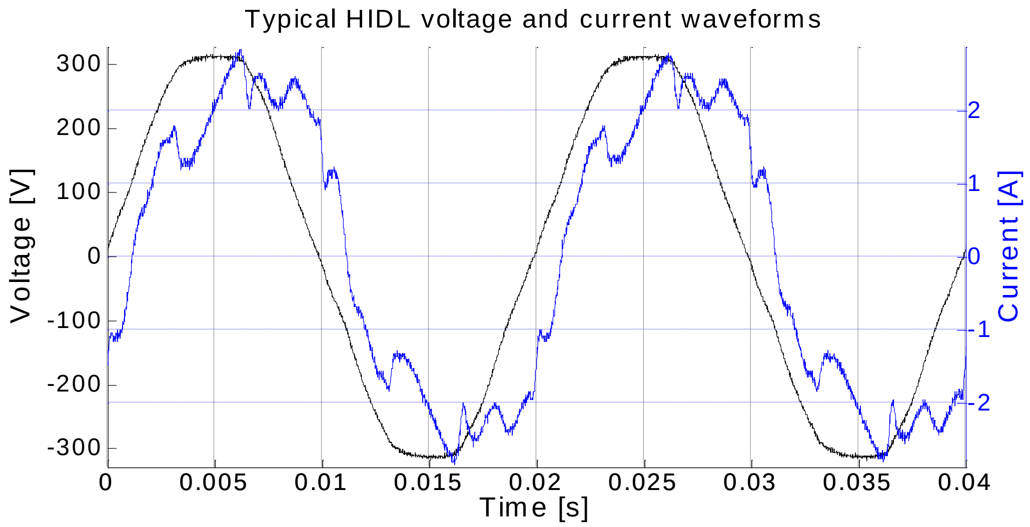

Figure 123: Typical supply voltage and current waveforms for a HIDL with a magnetic ballast.

3.7.3.2 Harmonic content of the supply current

Figure 124 and Figure 125 shows the harmonic spectrum of the current waveform for the HIDL sample 1 of each of the manufacturers considered in this chapter. The current spectrums exhibit a moderate amount of uneven harmonics.

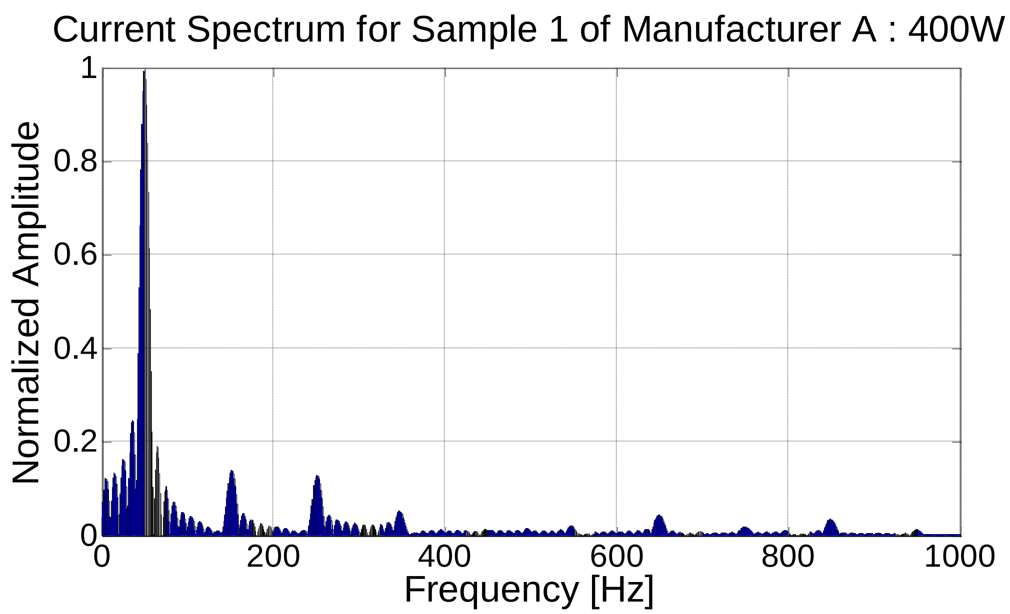

Figure 124: Current spectrum for the first 400W HIDL sample from manufacturer A and magnetic ballast alpha.

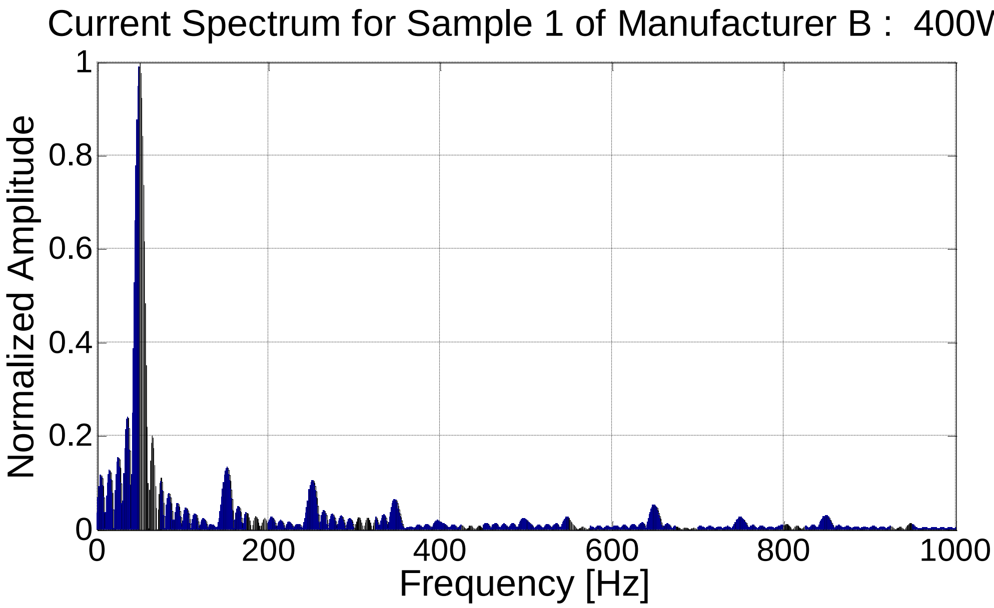

Figure 125: Current spectrum for the first 400W HIDL sample from manufacturer B and magnetic ballast alpha.

Table 20 illustrates the magnitude of the third harmonic relative to the fundamental for each of the tested HIDLs.

Table 20: Magnitudes of the 3rd harmonics, of the HIDLs considered in this chapter, for a supply voltage of 230V.

Manufacturer / Model	Ballast type	Ballast manufacturer	Power Rating [W]	Sample number	3rd Harmonic [%]
A	Magnetic	alpha	400	1	13.253
				2	12.944
				3	13.246
B	Magnetic	alpha	400	1	12.498
				2	12.514
				3	11.002

Figure 126 and Figure 127 show the THD of the supply current waveforms respectively as a function of the RMS supply voltage for various HIDL samples tested.

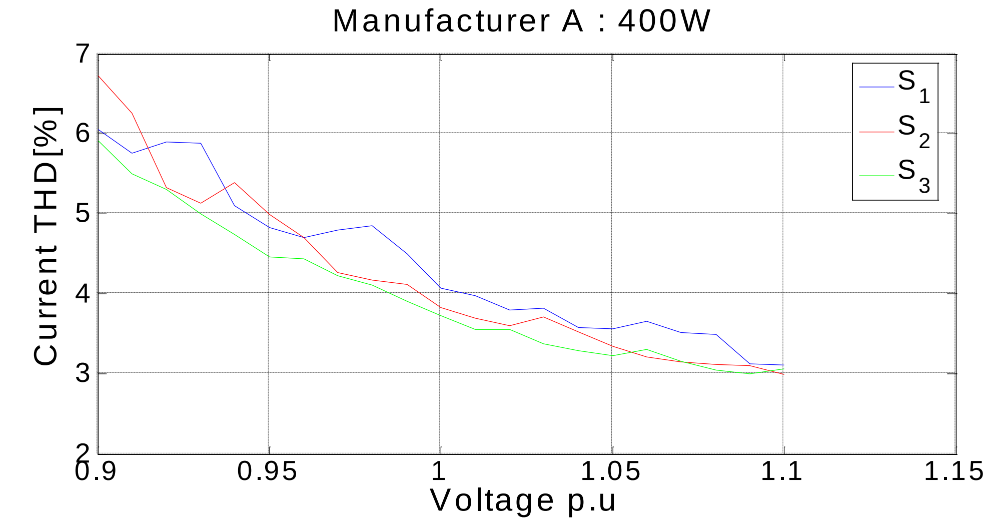

Figure 126: THD of the current waveform versus RMS supply voltage for 400 W HIDLs from manufacturer A and magnetic ballast alpha.

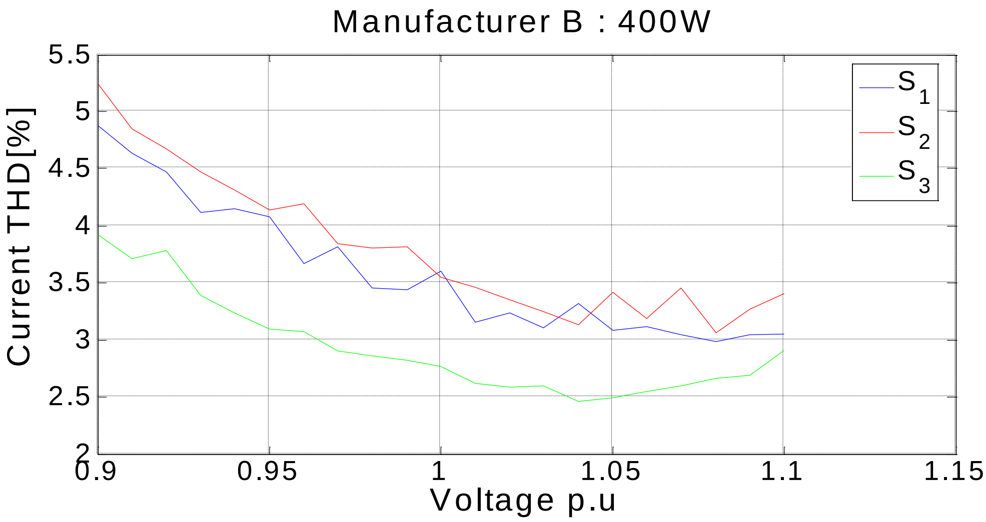

Figure 127: THD of the current waveform versus RMS supply voltage for 400 W HIDLs from manufacturer B and magnetic ballast alpha.

3.7.4 Zero sequence currents

3.7.4.1 Measurement results

Figure 128 to Figure 131 show the results for the three-phase supply current and neutral current waveforms respectively, at a supply voltage of 230V, for the HIDLs considered in this chapter.

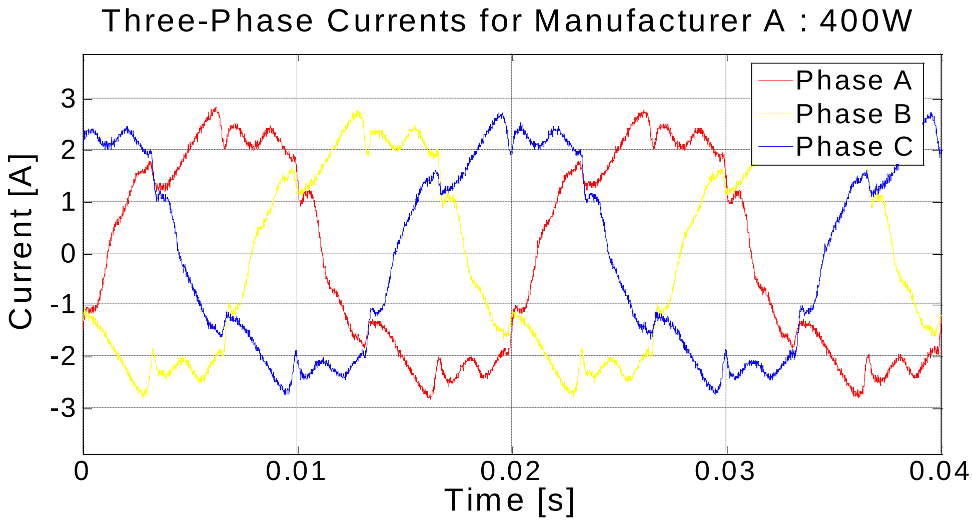

Figure 128: Three-phase current waveforms for the 400W HIDLs from manufacturer A and magnetic ballast alpha.

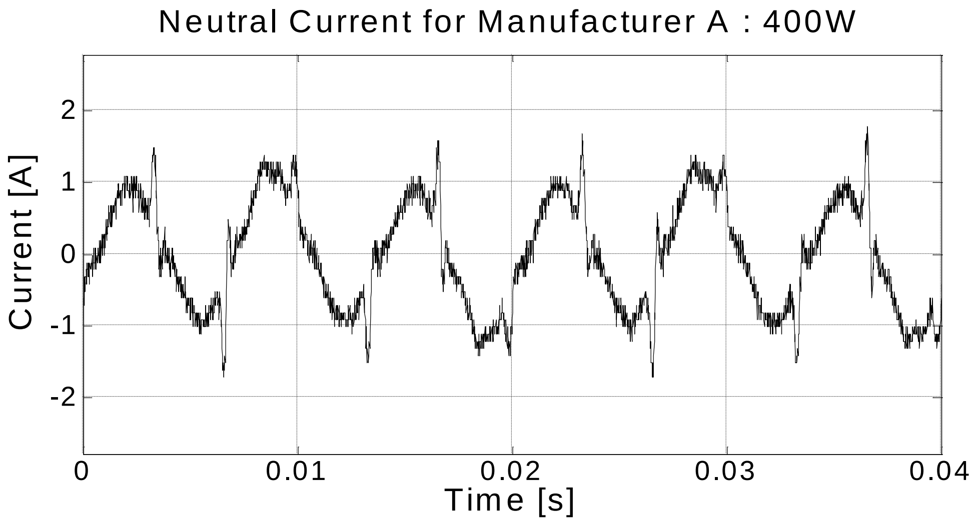

Figure 129: Neutral current waveform for the 400W HIDLs from manufacturer A and magnetic ballast alpha.

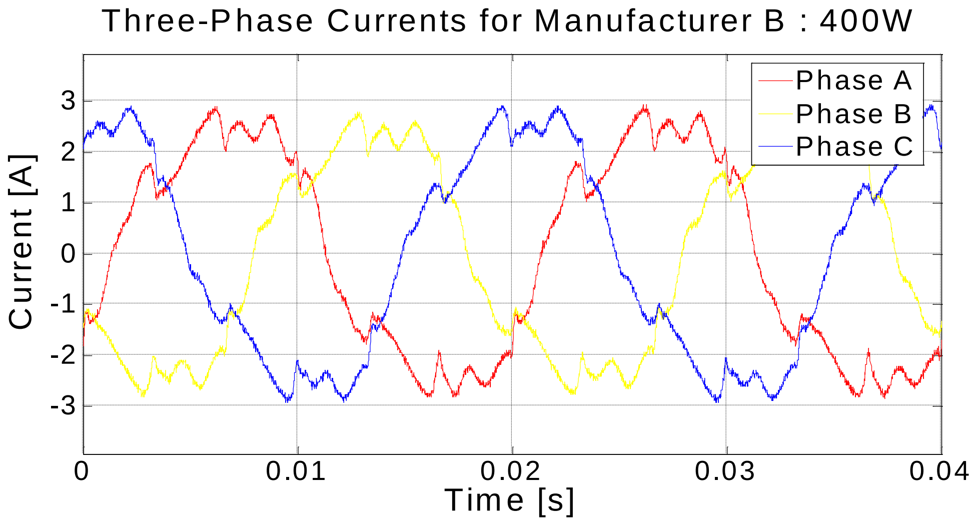

Figure 130: Three-phase current waveforms for the 400W HIDLs from manufacturer B and magnetic ballast alpha.

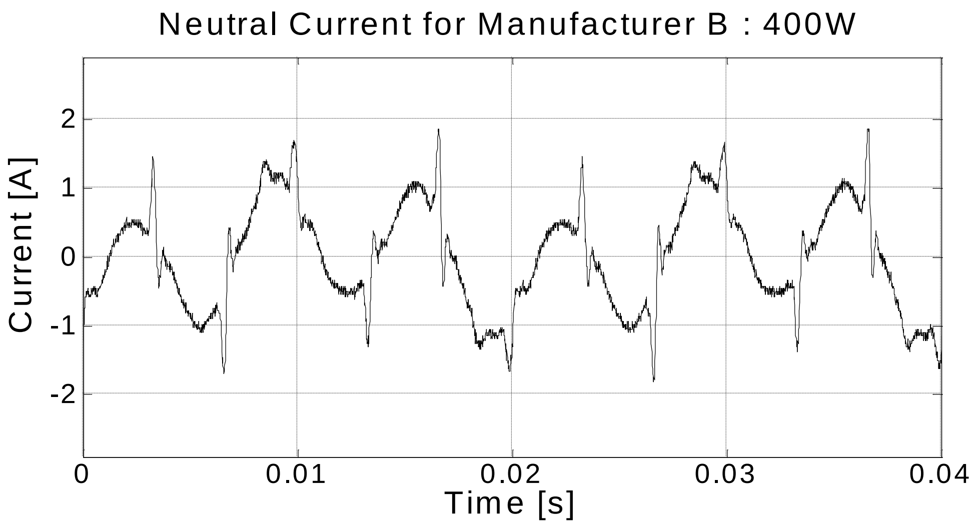

Figure 131: Neutral current waveform for the 400W HIDLs from manufacturer B and magnetic ballast alpha.

Figure 132 and Figure 133 show the results for the three-phase supply current and neutral current waveforms respectively for 400W HIDLs where the manufacturers are mixed.

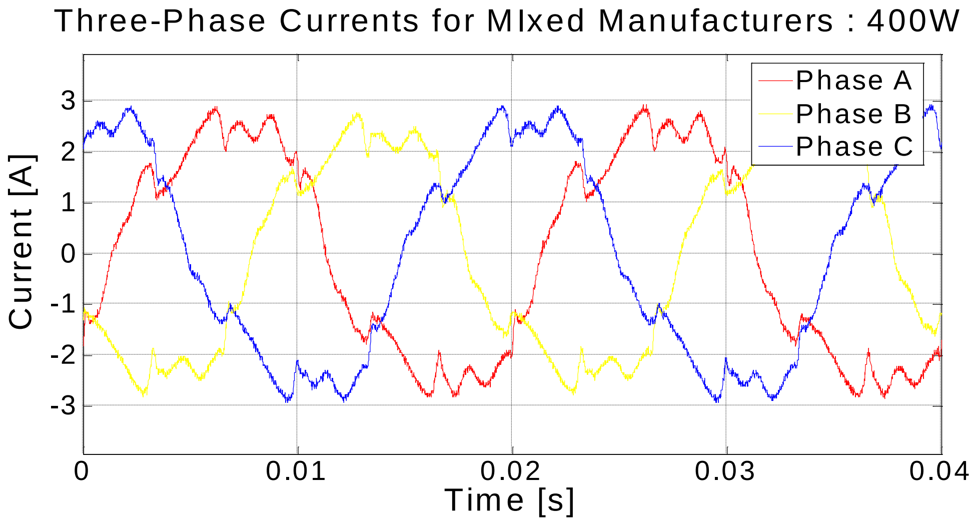

Figure 132: Three-phase current waveforms for the 400W HIDLs from mixed manufacturers.

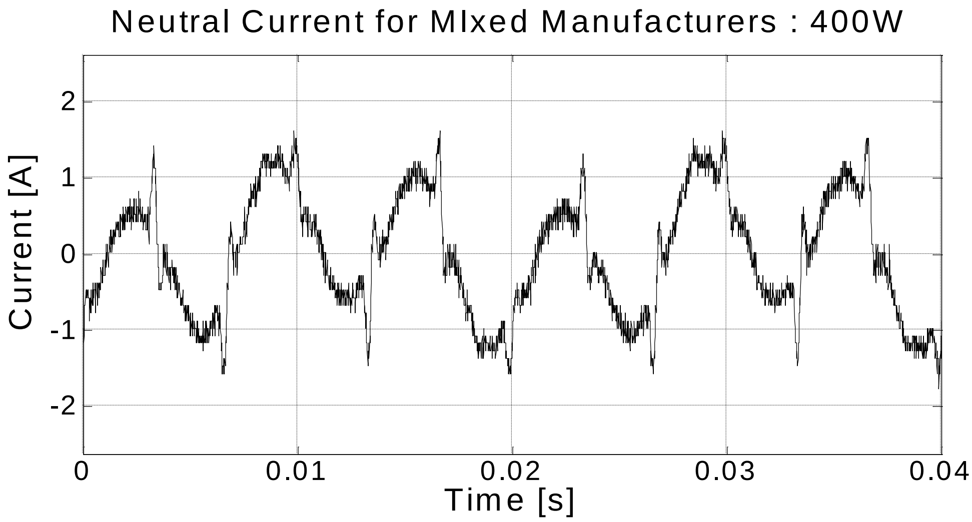

Figure 133: Neutral current waveform for the 400W HIDLs from mixed manufacturers.

Table 21 contains a comparison between the phase currents and the neutral currents of the HIDLs considered in this chapter.

Table 21: RMS neutral current vs. RMS phase current for HIDLs considered in this chapter.

Manufacturer / Model	Ballast	Power Rating [W]	RMS Phase A Current [A]	RMS Phase B Current [A]	RMS Phase C Current [A]	RMS Neutral Current [A]
A	Alpha	400	1.894	1.845	1.842	0.7883
B	Alpha	400	1.975	1.895	2.002	0.7826
Mixed (A,B,A)	Alpha	400	-	-	-	0.7756

3.8 Conclusions

The results contained in this report are only applicable to the lighting technologies represented in this report. The results are obtained from new samples only.

3.8.1 Incandescent lamps

3.8.1.1 Power consumption of ILs

The relationship between the active power consumption of ILs and the magnitude of the supply voltage differs from the square-law relationship normally assumed for ILs. This could be attributed to the filament having some of the properties of a thermistor (see section 2.1.2). Table 22 shows the power consumption, as a percentage of the rated power, at 207 V, 230 V and 253 V respectively.

Table 22: Power consumption for the different ILs at 207 V, 230 V and 253 V respectively.

Manufacturer / Model	Power Rating [W]	Sample number	% of rated power		
			at 207 V	at 230 V	at 253 V
A	60	1	82.17	96.17	111.17
		2	81.83	96.33	111.5
		3	82.67	96.67	111.83
	100	1	80.5	93.5	108.2
		2	79.9	93.5	108.3
		3	80.3	94.1	108.7
B	60	1	80	94.33	109.17
		2	79	92.5	107.17
		3	79.83	94.17	108.67
	100	1	80.1	94.1	109.1
		2	80.7	93.9	108.6
		3	81.2	94.1	108.6
C	60	1	86.33	101.33	117
		2	83.5	97.67	112.83
		3	83	96.83	111.67
	100	1	81.3	95.5	110.5
		2	82.2	95.6	110.6
		3	85.1	98.5	114.2

The RMS current and apparent power measurements show linear trends. The power factor and reactive power measurements are approximately constant.

3.8.1.2 Harmonic content of ILs

The IL supply current waveforms exhibit very low degrees of harmonic distortion, with THDs ranging from approximately 0.11 % to 0.18 % over the supply voltage range tested. The impact on QOS is thus insignificant.

3.8.1.3 Neutral current of ILs

The measured results for three-phase IL loads have shown that the ILs give rise to an insignificant amount of neutral current loading. The small amount of neutral current measured could be as a result of the slight unbalance of the three-phase supply voltage.

3.8.2 Compact fluorescent lamps

3.8.2.1 Power consumption of CFLs

The power consumption of CFLs as a function of supply voltage magnitude is approximately linear. Table 8 shows the power consumption, as a percentage of the rated power, at 207 V, 230 V and 253 V respectively.

Table 23: Power consumption for the different CFLs at 207 V, 230 V and 253 V respectively.

Manufacturer / Model	Power Rating [W]	Sample number	% of rated power		
			at 207 V	At 230 V	at 253 V
A	14	1	82.86	92.86	100.71
		2	82.86	90	107.14
		3	84.29	92.86	104.29
	20	1	83.0	92.50	105.0
		2	81.0	91.50	103.0
		3	81.50	91.50	110.50
B	14	1	85.71	92.86	106.43
		2	88.57	97.14	111.43
		3	86.42	95	108.57
C	14	1	77.14	87.86	99.29
		2	76.43	84.28	101.43
		3	72.86	80.71	95.0
	20	1	77.50	86.50	99.0
		2	81.50	84	95.0
		3	80.0	85	96.50
D	20	1	79.50	91	99.0
		2	82.50	92	100.0
		3	84.50	94	103.0

The RMS current measurements show an active response in the sense that the current usage increases only slightly as the supply voltage is increased. The reactive power and apparent power measurements show linear characteristics. The power factor measurements decrease slightly for an increase in supply voltage.

3.8.2.2 Harmonic content of CFLs

The supply current waveforms of the CFLs tested exhibit very high degrees of harmonic distortion, with the THD ranging from approximately 110 % to over 250 % over the supply voltage range tested. This gives rise to additional heat losses in the supply network, especially distribution transformers [16]. If the CFL load forms a substantial amount of the overall load, it could lead to voltage distortion at the point of common coupling [17]. A substantial CFL load could lead to a decrease in power factor of the system [18].

3.8.2.3 Neutral current of CFLs

The measured results for three-phase CFL loads have shown that the CFLs give rise to high zero-sequence, i.e. neutral current loading. This is a potential cause for concern, especially for underrated networks. The practical implications of the increased neutral current loads are increased voltage distortion at the consumer supply points, overheating of neutral conductors and connections, shift of the neutral voltage with respect to earth potential (with possible safety implications) and interference with protection schemes [19]. Overall, the severity of these effects is dependent on the relative CFL load rating, actual network ratings and network operating conditions.

3.8.3 Tubular fluorescent lamps with magnetic ballasts

3.8.3.1 Power consumption of TFLs with magnetic ballasts

The power consumption of TFLs with magnetic ballasts, as a function of supply voltage magnitude is approximately linear. Table 24 shows the power consumption, as a percentage of the rated power, at 207 V, 230 V and 253 V respectively. TFLs with magnetic ballasts show a maximum deviation of 47 % from the rated power. This could impact on energy saving calculations [20].

Table 24: Power consumption for the different TFLs at 207 V, 230 V and 253 V respectively.

Manufacturer / Model	Ballast type	Ballast manufacturer	Power Rating [W]	Sample number	% of rated power		
					at 207 V	at 230 V	at 253 V
A	Magnetic	alpha	36	1	96.39	120	147.5
				2	95.56	120.28	147.22
				3	95	119.72	147.5
			58	1	85.69	114.48	140.69
				2	91.72	118.97	145.51
				3	86.55	114.66	141.55

B	Magnetic	alpha	36	1	96.94	120.28	147.5
				2	96.11	120.83	148.61
				3	96.67	120.56	148.89
			58	1	88.62	115.34	140.51
				2	93.10	120.17	145.68
				3	87.59	115	141.03

The reactive power measurements of the 36 W power rating shows an increase as the supply voltage increases. The reactive power measurements for the 58 W power rating show the opposite trend i.e. it decreases as the voltage increases.

3.8.3.2 Harmonic content of TFLs with magnetic ballasts

The supply current waveforms of TFLs with magnetic ballasts exhibit moderate degrees of harmonic distortion, with THDs ranging from approximately 10% to 22% over the supply voltage range tested. The overall impact on QOS is expected to be low.

3.8.3.3 Neutral current of TFLs with magnetic ballasts

The measured results for three-phase TFLs, with magnetic ballasts, have shown that the TFLs, with magnetic ballasts, give rise to a moderate amount of neutral current loading. The RMS neutral current present is over half the RMS current of one phase. This a potential cause for concern depending on network ratings.

3.8.4 Tubular fluorescent lamps with electronic ballasts

3.8.4.1 Power consumption of TFLs with electronic ballasts

The power consumption of TFLs with electronic ballasts, as a function of supply voltage magnitude, is approximately linear. Table 25 shows the power consumption, as a percentage of the rated power, at 207 V, 230 V and 253 V respectively. TFLs with electronic ballasts show a maximum deviation of 19 % from the rated power. This could impact on energy saving calculations.

Table 25: Power consumption for the different TFLs at 207 V, 230 V and 253 V respectively.

Manufacturer / Model	Ballast type	Ballast manufacturer	Power Rating [W]	Sample number	% of rated power		
					at 207 V	at 230 V	at 253 V
A	Electronic	alpha	36	1	90.56	101.39	113.06
				2	88.61	99.167	110.06
				3	93.06	105.56	118.33
			58	1	85.34	95.35	105.69
				2	82.41	91.21	100.52

				3	84.83	94.48	104.66
B	Electronic	alpha	36	1	88.61	99.44	110.56
				2	90.28	98.89	110
				3	90.56	99.44	111.11
			58	1	81.55	90.517	99.83
				2	81.72	90.86	99.82
				3	83.27	92.5	102.24

The RMS current measurements show a linear characteristic, however the variation in current consumption is well below 10 %, thus it could also be characterised as approximately constant. The apparent power measurements show linear characteristics, with both sets of measurements increasing as the supply voltage increases. The power factor measurements show an inconsistent trend but show a deviation of less than 5 % which would indicate that it is approximately constant.

3.8.4.2 Harmonic content of TFLs with electronic ballasts

The supply current waveforms of TFLs with electronic ballasts exhibit moderate to low degrees of harmonic distortion, with THDs ranging from approximately 0.5 % to 2.5 % over the supply voltage range tested. This is not expected to have any significant impact on QOS.

3.8.4.3 Neutral current of TFLs with electronic ballasts

The measured results for three-phase TFL with electronic ballasts have shown that the TFLs give rise to moderate to low zero-sequence, i.e. neutral current loading. RMS neutral currents are at approximately 25 % of the RMS current in one phase.

3.8.5 High intensity discharge lamps

3.8.5.1 Power consumption of HIDLs with magnetic ballasts

The power consumption of HIDLs with magnetic ballasts, as a function of supply voltage magnitude, is approximately linear. Table 26 shows the power consumption, as a percentage of the rated power, at 207 V, 230 V and 253 V respectively.

Table 26: Power consumption for the different HIDLs at 207 V, 230 V and 253 V respectively.

Manufacturer / Model	Ballast manufacturer	Power Rating [W]	Sample number	% of rated power		
				at 207 V	at 230 V	at 253 V
A	alpha	400	1	72	93.25	114.5
			2	70.25	89	109.5

			3	69.25	88.5	109.5
B	alpha	400	1	75.5	93.25	114
			2	71.25	89.75	110
			3	71.25	88.25	108.5

The RMS current, reactive power and apparent power measurements show a linear characteristic. They show an increase as the supply voltage increases. The power factor shows a linear decrease as the supply voltage increases.

3.8.5.2 Harmonic content of HIDLs with magnetic ballasts

The HIDL supply current waveforms exhibit moderate to low degrees of harmonic distortion, with THDs ranging from approximately 2.5 % to 7 % over the supply voltage range tested.

3.8.5.3 Neutral current of HIDLs with magnetic ballasts

The measured results for three-phase HIDLs with magnetic ballasts have shown that the HIDLs give rise to moderate neutral current loading. RMS neutral currents are at approximately 41 % of the RMS current in one phase. This is a potential cause for concern depending on network ratings.

4. Profile Gathering

4.1 Introduction

Artificial-light usage profiles, and to a lesser extent voltage profiles, play an important role when determining the savings of EE lighting projects. The effect of the supply voltage in assessing the impacts of EE lighting projects is dependent on the voltage dependency of the lighting technologies associated with the project. It is thus not necessarily a critical factor when assessing EE lighting projects. Artificial-light usage however, plays an important role in determining the savings of EE lighting projects, especially when determining energy savings as opposed to determining load reductions.

This chapter investigates the method(s) commonly used to obtain artificial-light usage profiles and voltage profiles.

4.2 Voltage profiles

Voltage profiles are recorded using data loggers capable of measuring RMS voltage and storing the measured data sampled over a period of time. The voltage is logged at a user defined interval. The data retrieved from the logger is processed so as to deliver a half-hourly averaged RMS voltage profile, as is shown in Figure 134.

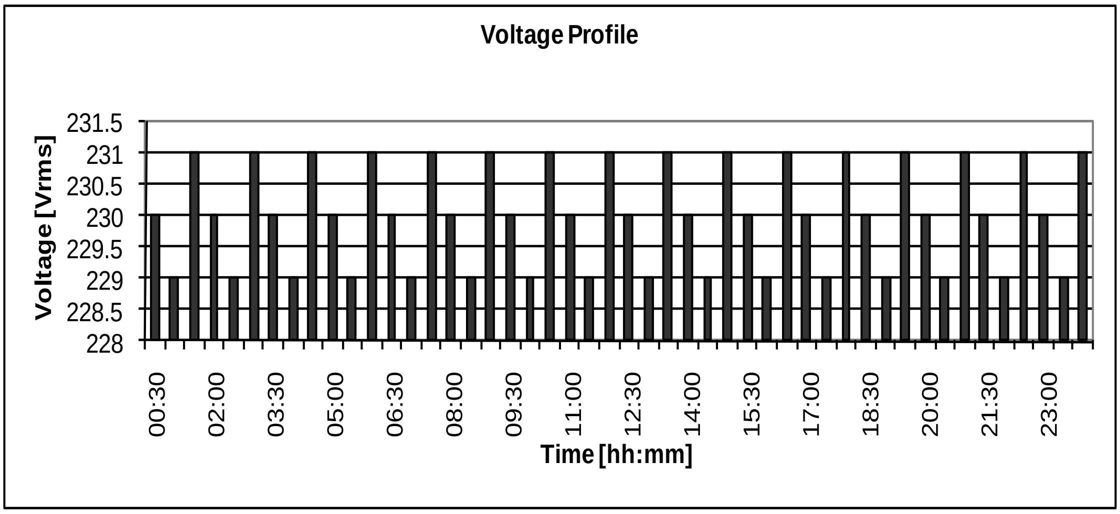

Figure 134: Example of a half-hourly averaged RMS voltage profile.

4.3 Artificial-light usage profiles

The following three methods for obtaining an artificial-light usage profile are investigated:

- *Artificial-light usage survey:* This method requires that people are interviewed and asked about their artificial-light usage habits. The data obtained by this method is not based on scientific measurements and therefore its accuracy can be easily contested.
- *Daylight modelling:* This method can be implemented if the lighting technologies are being controlled by daylight switches. This method involves obtaining the sunrise and sunset times of the area in which the project site is located. The artificial-light usage profiles are then determined based on these times. The accuracy of this method is dependent on the quality of the technology as well as the correct application the technology.
- *State change sensors:* This method utilises state-change detection sensors. Sensors detect state changes, i.e. lights being switched on or off, and stores the event and state. If implemented correctly this method provides accurate data pertaining to the artificial-light usage. Chapter 4.3.1 investigates the application of a state-change sensor.

Artificial-light usage profiles are typically normalized to unity. This factor is determined by the amount of lighting technologies which is switched on, relative to the total number of lighting technologies attributed to that sectional area. Figure 139 shows an example of a half-hourly artificial-light usage profile.

4.3.1 Hobo® u9-002 light on/off data logger

4.3.1.1 About the Logger

The “Hobo U9-002 Light on/off” data logger (see Figure 135) logs state changes that occur when lights are switched on or off.

Figure 135: Hobo U9-002 Light on/off data logger.

The sensor is directional, with the highest sensitivity in the forward direction. The sensor also has a minimal amount of sensitivity to the sideways direction, thus it is also susceptible to light coming from the side [21].

Figure 136 shows a plot of the light sensors angular response, obtained from the logger's datasheet. The logger also has an adjustable sensitivity threshold. The threshold can be set between 10 lumens/m^2 and 100 lumens/m^2 [21].

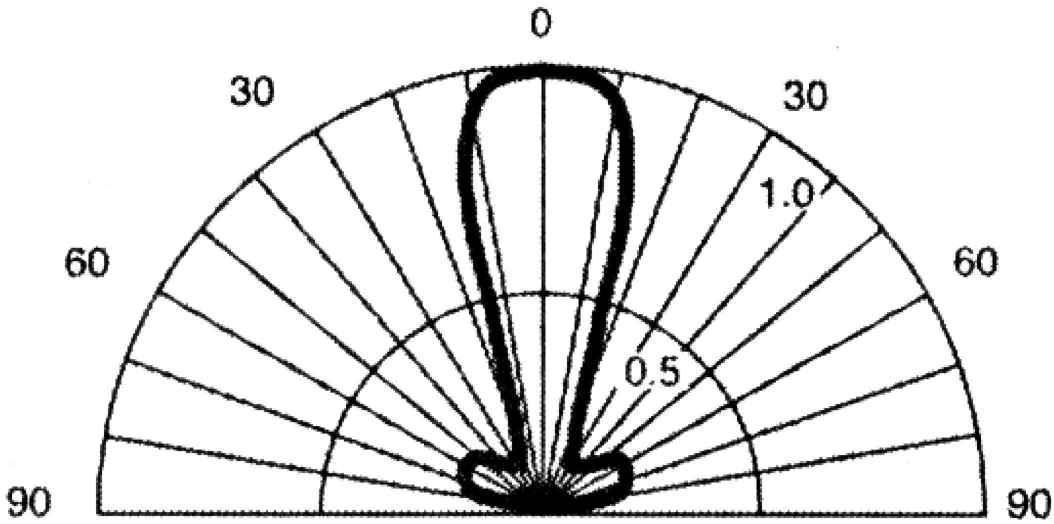

Figure 136: Light sensor's angular response [21].

4.3.1.2 Deploying the logger

The Hobo® u9-002 light on/off data logger was deployed in a university laboratory/work area. The Hobo® u9-002 light on/off data logger is placed in a light fixture containing two 75 W fluorescent tubes. This light fixture is furthest away from the window in order to minimize the effects of natural light on the sensor. The sensor's sensitivity is adjusted to maximize the accuracy of the readings for the sensor's orientation within the light fixture. Figure 137 shows the orientation of Hobo® u9-002 light on/off data logger within the light fixture.

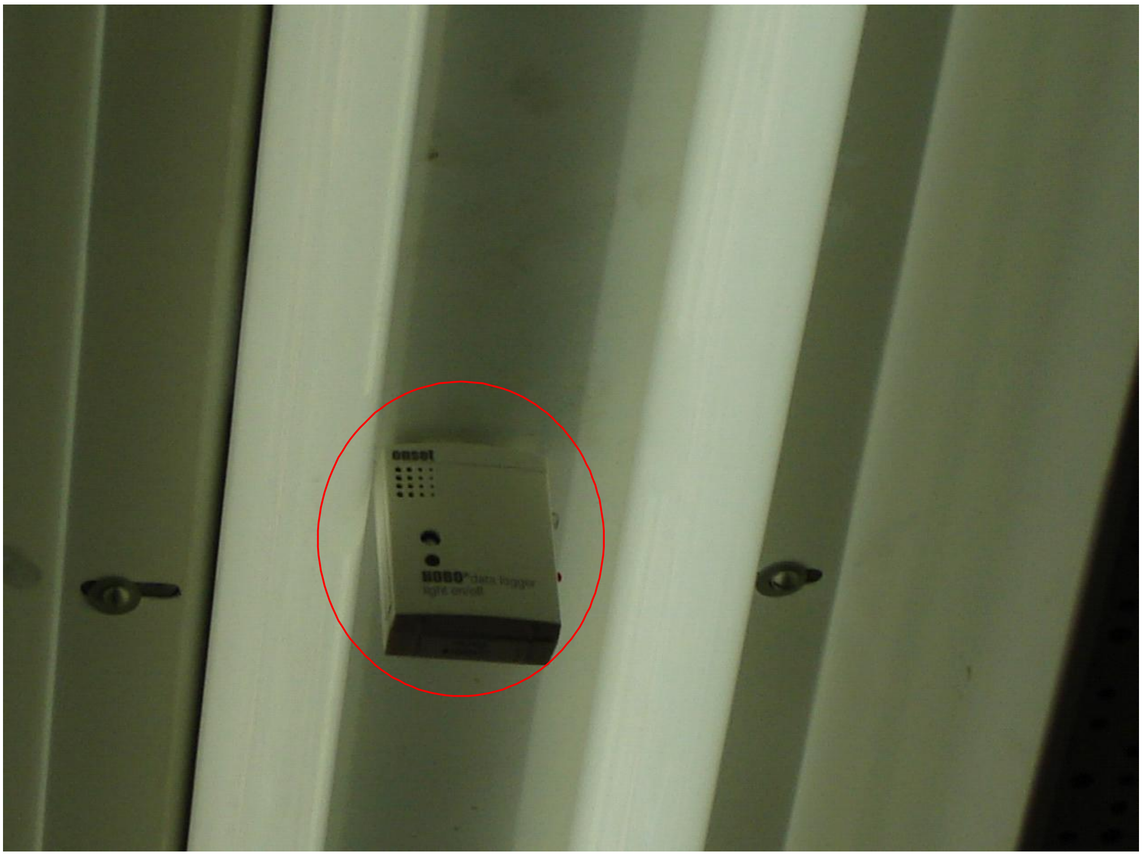

Figure 137: Orientation of Hobo® u9-002 light on/off data logger within the light fixture.

4.3.1.3 Output data

Figure 138 shows the output data from the Hobo® u9-002 light on/off data logger for February 2008.

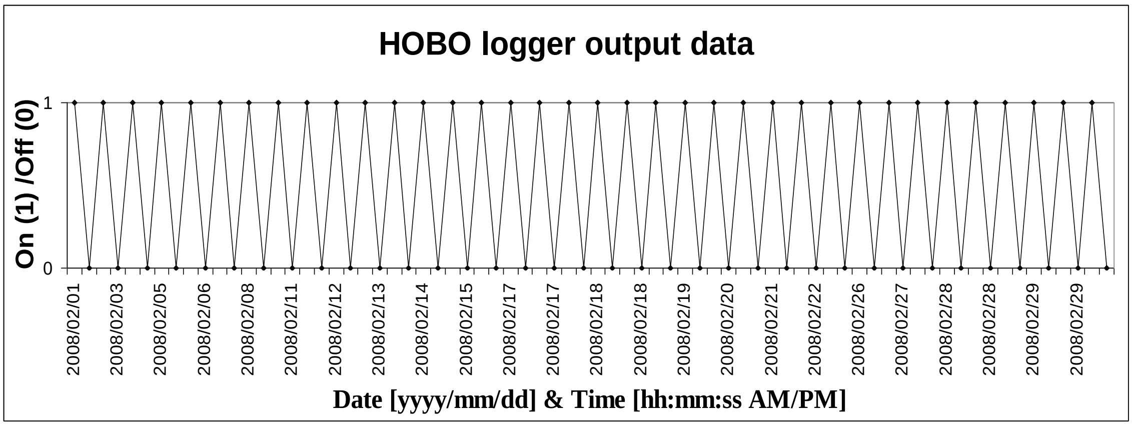

Figure 138: Unprocessed output data.

All of the lighting technologies in the laboratory are on the same on/off switch, thus the artificial-light usage factor is one if they are on for any one of the defined half-hour periods. If a state change occurs within one of the defined half-hour periods the artificial-light usage factor is adjust by determining an average over the specific half-hour period.

Figure 139 to Figure 141 show the average weekday, average Saturday and average Sunday, artificial-light usage profiles compiled from the output data from the Hobo® u9-002 light on/off data logger.

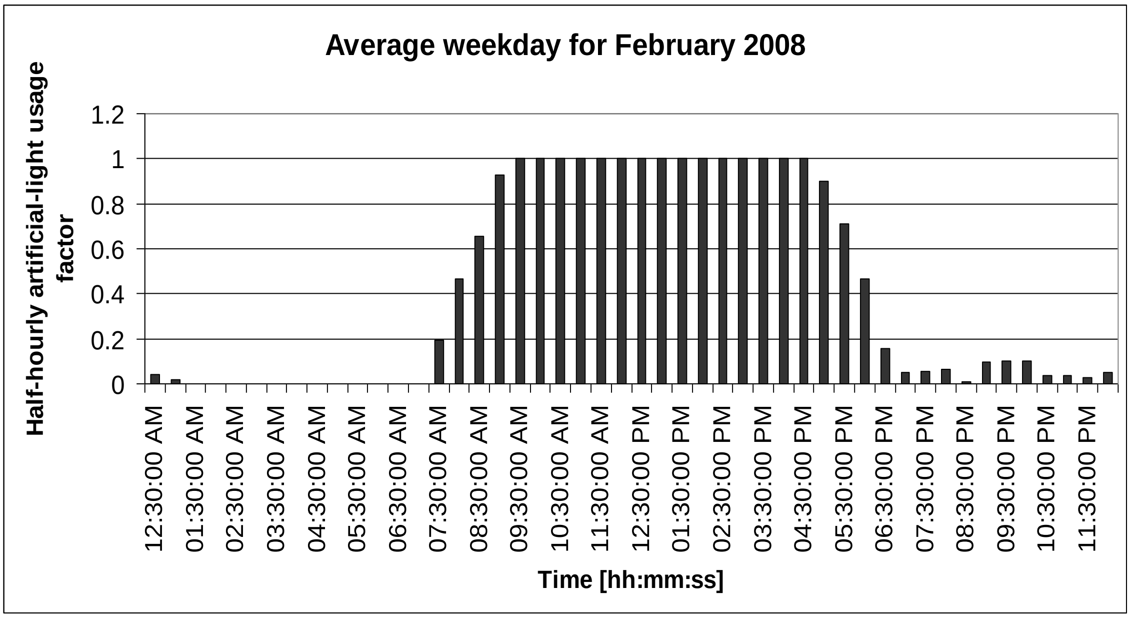

Figure 139: Average weekday artificial-light usage profile based on the output data.

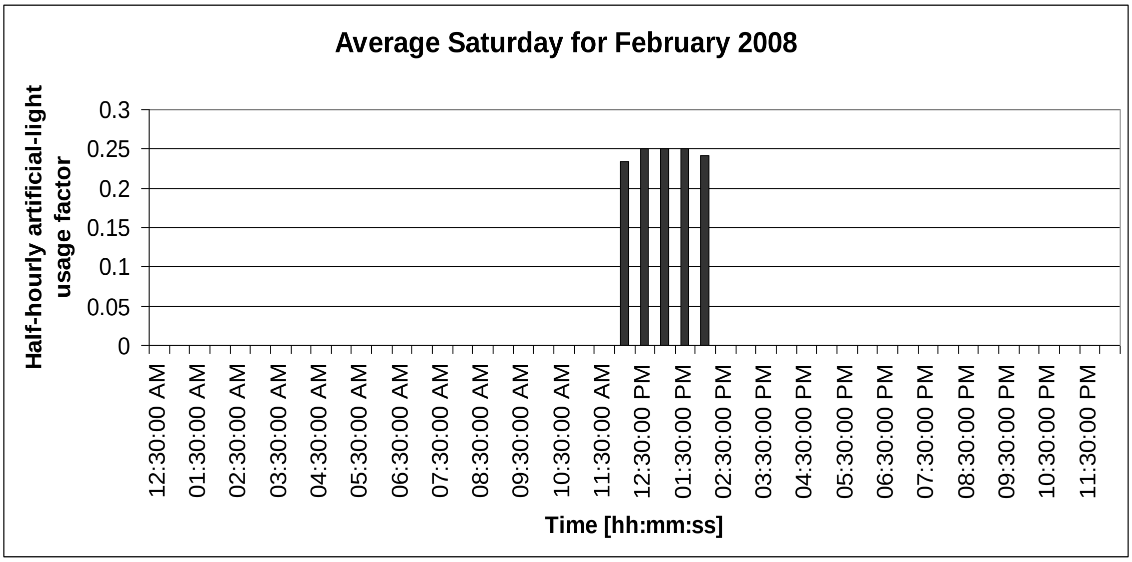

Figure 140: Average Saturday artificial-light usage profile based on the output data.

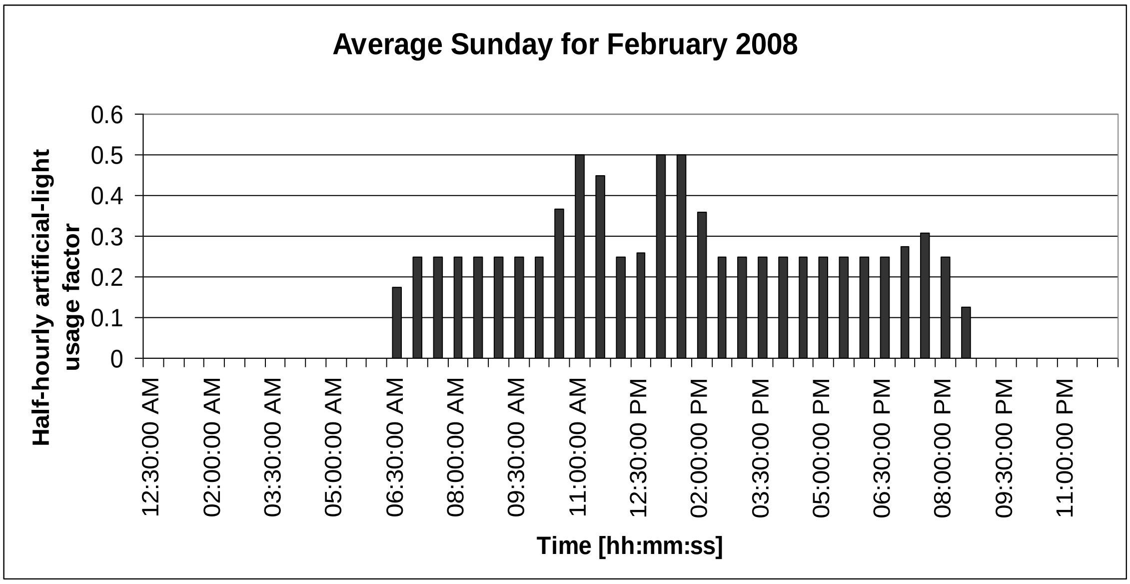

Figure 141: Average Sunday artificial-light usage profile based on the output data.

4.4 Conclusions

Given the correct equipment and the correct application thereof, obtaining accurate voltage profiles and artificial-light usage profiles is achievable. A certain amount of post-processing is required. When using state change loggers, the deployment off the loggers might need to be customized to the specific project site. In the case off the Hobo® u9-002 light on/off data logger, avoiding direct exposure to natural light is a necessity.

5. DSM Lighting Projects Software Tool

5.1 Introduction

The Lighting Projects Software Tool (LPST) was developed in the Borland® Delphi environment while the database support and structures were developed in the MySQL environment. The main functions of the LPST are as follows:

- The LPST is to be utilized by multiple users with most of the data to be stored and retrieved from one central database.
- Each user has access to their own data as well as data provided by the database host. The user will thus create and store their own data as well as use data provided by the database host.
- The LPST serves as a database which contains technical information of various lighting technologies as well as details of voltage and light usage profiles. It also contains EE lighting project information.
- The LPST can be used to calculate the active energy demand as a result of artificial spatial lighting of any site given the necessary input information.

  The ISP is able to generate the following output data:

  - Half hourly active energy usage of relevant lighting technologies over a user defined period.
  - Information pertaining to the project case.

The LPST requires various inputs in order to deliver its output of a half-hourly active energy usage and half-hourly active energy savings profiles. The following data is required in order to deliver the required output:

- Mathematical models of the various lighting technologies associated with a project.
- Half-hourly averaged supply voltage profiles associated with a project.
- Half-hourly averaged artificial-light usage profiles of the lighting technologies associated with a project.
- The amount of the specific lighting technology that is used.

The LPST also performs general graphical user interface (GUI) functions, i.e. opening and saving files, copying and saving graphs, as well as exporting data to Microsoft Excel. The files are saved in text format and are assigned a file extension local to the LPST. The graphs are saved as bitmap files. Descriptive information, i.e. information that isn't used in any calculations, is also stored in the database.

The GUI is required to implement the following functions:

- Communicate with a database.
- Calculate active energy usage and savings in order to assess EE lighting projects.
- Load and store project/cases and results.
- Display results.

The database is required to fulfil the following criteria:

- A reasonably fast query speed.
- The ability to interact with multiple users.
- Reasonably low cost of the software package as well as licensing, if needed.
- A suitable storage capacity for practical implementation.
- Good data security and database stability.
- Data backup capability.

5.2 Software structure

5.2.1 Overview

The LPST software package has two components, namely the graphical user interface (GUI) and the SQL database, as illustrated in Figure 142.

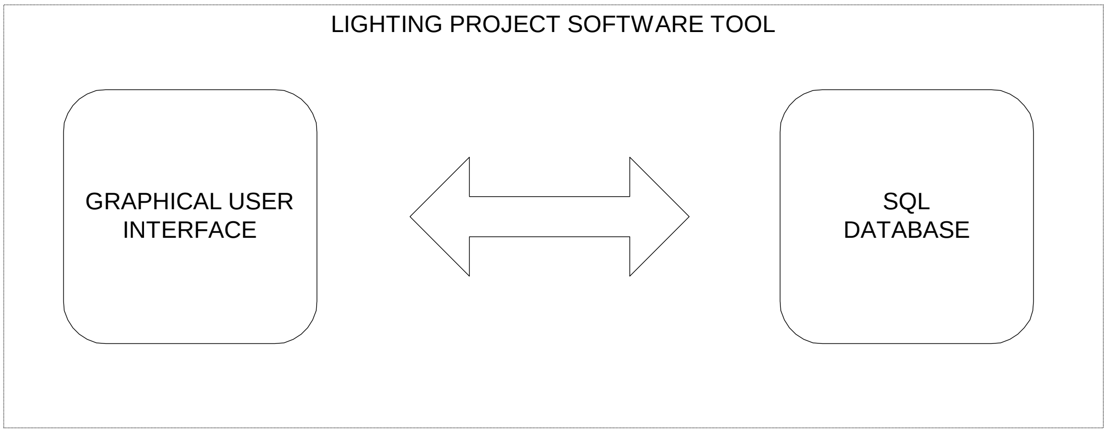

Figure 142: Two components of the LPST.

5.2.2 SQL database

The database structure for the LPST is a reasonably simple one. The main inputs to the LPST, i.e. voltage profile, artificial-light usage profiles and lighting technology information are stored independently in their own tables within the database. As certain lighting technologies involve two separate components, e.g. a lamp and ballast, the tables containing their data are relational to each other [22]. The LPST makes provision for an internal database (created by the user) of light usage profiles as well as an external database (created by the database host) of light usage profiles. However, the data for these profiles are all stored within the same table.

The SQL database of the LPST consists of the following tables:

- Lamp data.
- Ballast data.
- Profile data.
- Public holiday information.

5.2.3 User interface

The Graphical User Interface (GUI) consists of a number of forms/pages. Each form has its own function within the GUI.

Figure 143 shows how the key forms are accessed and what function they perform or what information they display. Appendix B contains a user's manual, which illustrates how the GUI should be used.

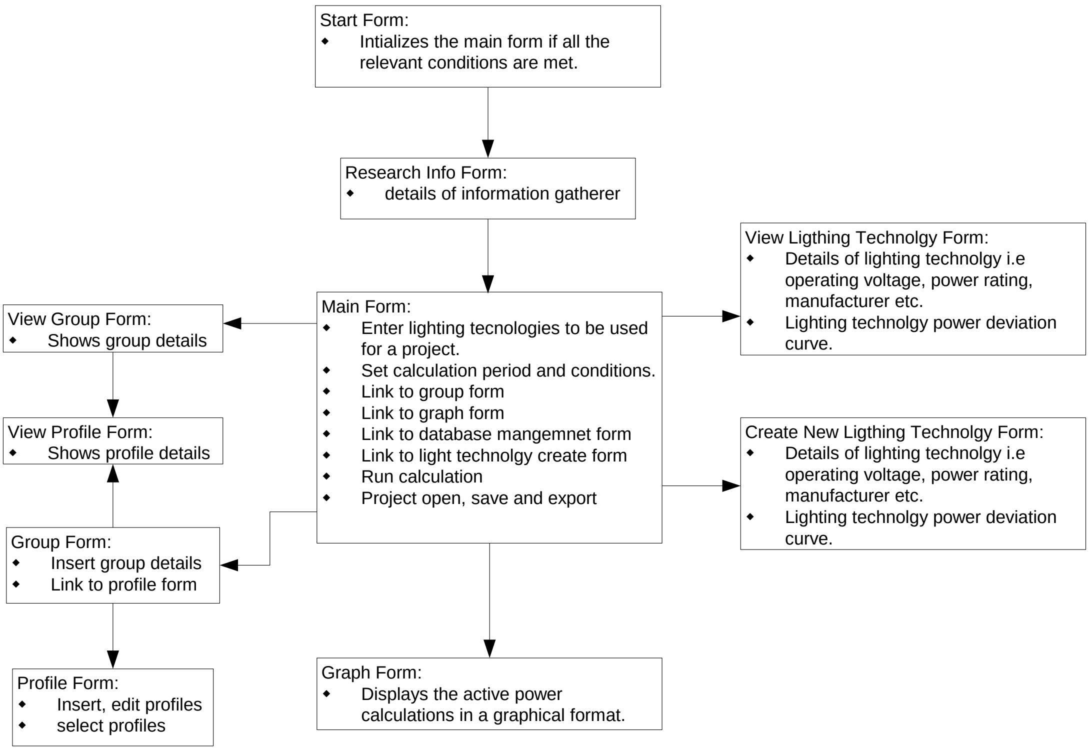

Figure 143: GUI forms.

Global functions are accessed by means of buttons on the active form(s). Functions can be accessed by other functions as well as through the active form directly. This is done to facilitate an easier method of testing and debugging the functions and the associated code. Functions are also accessed by events, such as clicking on an object other than a button. These functions are usually local to that event only, and are rarely if ever called within other functions.

Global variables are realised by utilizing text labels, button captions or string grids that are placed on the GUI forms. This is done to give a visual account of the data calculated or stored, when debugging or testing code. The visibility property of these objects is set to false when the code has been tested and found to be working as required. This method requires extra commands to transform text data into numerical data.

Figure 144 shows a diagram of the main process of the GUI.

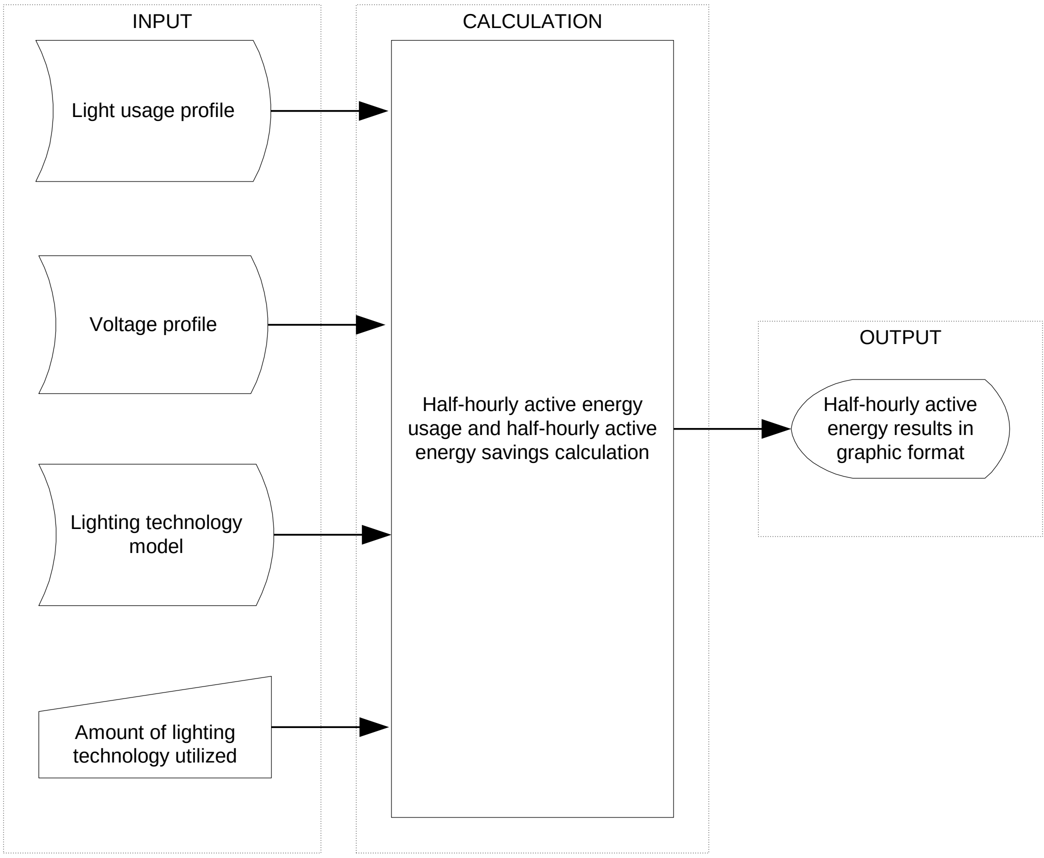

Figure 144: A diagram of the process for delivering the half-hourly active energy usage and half-hourly active energy savings data.

5.2.3.1 Half-hourly averaged artificial-light usage and supply voltage profiles

The artificial-light usage and voltage profile information consist of the following two types:

- Descriptive information.
- Data information.

The descriptive information consists of detail such as the name of the profile, where it was taken, the period for which it was gathered, a description of the conditions or methods by which it was gathered, etc. The data information consists of 48 data-points which represents the 48 half-hour periods within 24 hours. The descriptive information as well as the data information is stored as text strings or memo fields in the same table within the allocated database. Numerical data is converted from text format to numerical format by the GUI program.

Figure 134 and Figure 139 show examples of a voltage profile and an artificial-light usage profile respectively.

5.2.3.2 Voltage-dependent energy consumption models of the various lighting technologies

The voltage-dependent energy consumption modelling of the various lighting technologies is done as described in section 3.3. The implementation of the formula is done by utilizing a workbook component of the GUI development software. The workbook component functions in much the same manner as Microsoft Excel does, whereby formulas can be written using workbook cells as variables within those formulas, with the output of those formulas presented in the workbook cell that contains the formula. Utilizing this function it is possible to implement any mathematical formula, as long as the correct workbook cell is used as the variable within the formula and the correct programming language is used.

The formula is created in a text box and is stored as a text string within the table that contains the relevant lighting technology. When required the text string is retrieved from the database and is interpreted within the workbook component and the relevant calculations are made, the results of which is exported from the workbook component to the GUI. The output of the model is active power when the input is voltage. Thus when the half-hourly average voltage profile is the input, the resulting output, is a half-hourly active energy consumption profile.

5.2.3.3 Calculation process

The half-hour active energy usage is calculated by the relationship

$$E_{ave_{1/2h}} = F(V_{RMS_{ave_{1/2h}}}) \times \beta \times k \quad , \qquad [5.1]$$

where $F(V_{RMS_{ave_{1/2h}}})$, represents the active energy output of the model as a result of the average RMS voltage input, $V_{RMS_{ave_{1/2h}}}$, β represents the half-hourly light usage profile and k represents the number of the relevant lightfittings. Figure 156 shows an example of an active energy usage profile for a 24 hour period.

5.3 Program implementation of measurement and verification methodology for EE lighting projects

In order to successfully implement the measurement and verification methodology for assessing EE lighting projects (section 2.2.3), the LPST has to make provision for the following conditions:

- Voltage-dependent energy consumption characteristics of different lighting technologies.
- Sectional areas with different light usage profiles.
- Condonable days (see section 2.2.3).

The following sections describe how the GUI manages and implements these conditions.

5.3.1 Energy consumption characteristics of different lighting technologies

Once the specific lighting technology is modelled as described in section 3.3 and a mathematical relationship is obtained, the formula is stored in the SQL database along with other technical information for that specific lighting technology. When calculating a half-hourly active energy consumption profile by using a half-hourly averaged voltage profile together with the mathematical model, the model is retrieved from the database, applied to the voltage profile and the active energy profile is obtained. Figure 145 shows a flowchart of the implementation of this profile.

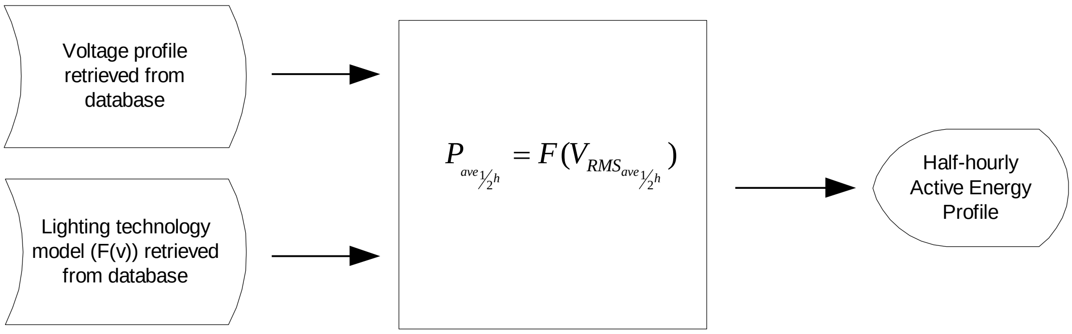

Figure 145: Flow diagram of the implementation of the half-hourly active energy consumption profile calculation by the GUI.

5.3.2 Sectional areas

The GUI makes provision for areas of a project site to have different types of artificial-light usage profiles. Each area is assigned descriptive details along with a voltage profile and artificial-light profiles for each day of the week. The following information is required when completing a sectional area form:

- Number and types of pre-implementation and/or post-implementation light fittings for the sectional area.
- A voltage profile.
- Artificial-light profiles for each day of the week.
- If applicable, artificial-light usage profiles for public holidays and/or condonable days are also required.

A grid matrix is created which contains the weekly artificial-light usage profiles, as well as the voltage profile for the sectional area. Figure 146 illustrates the sectional area profile grid matrix.

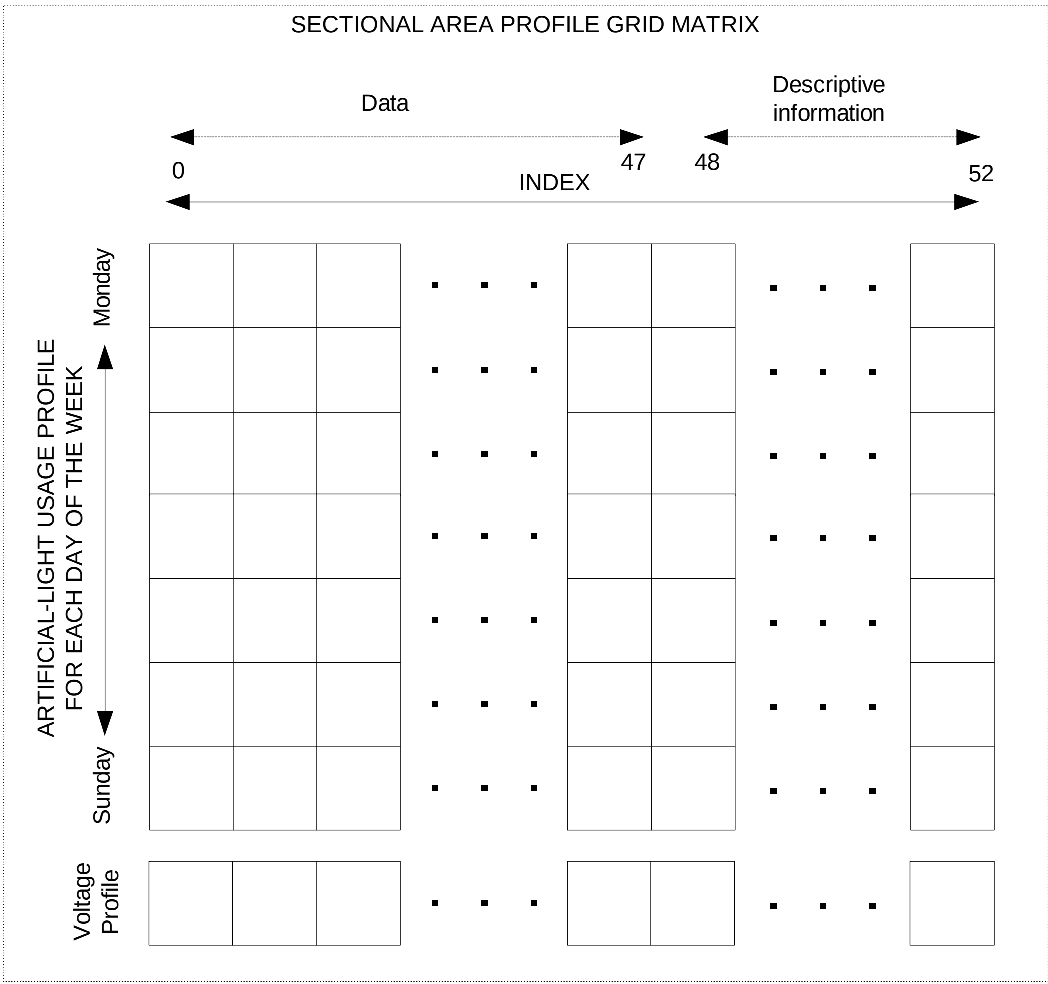

Figure 146: Illustration of the profile grid assigned to each sectional area.

Using equation 5-1, the half-hourly averaged active energy consumption profile for the data compiled in the sectional area page is calculated and stored within a pre-implementation and/or post-implementation grid matrix. The calculation results are for the period stated by the user. Figure 147 illustrates how the implementation grid matrix is utilised to store the active energy profiles for a user defined period.

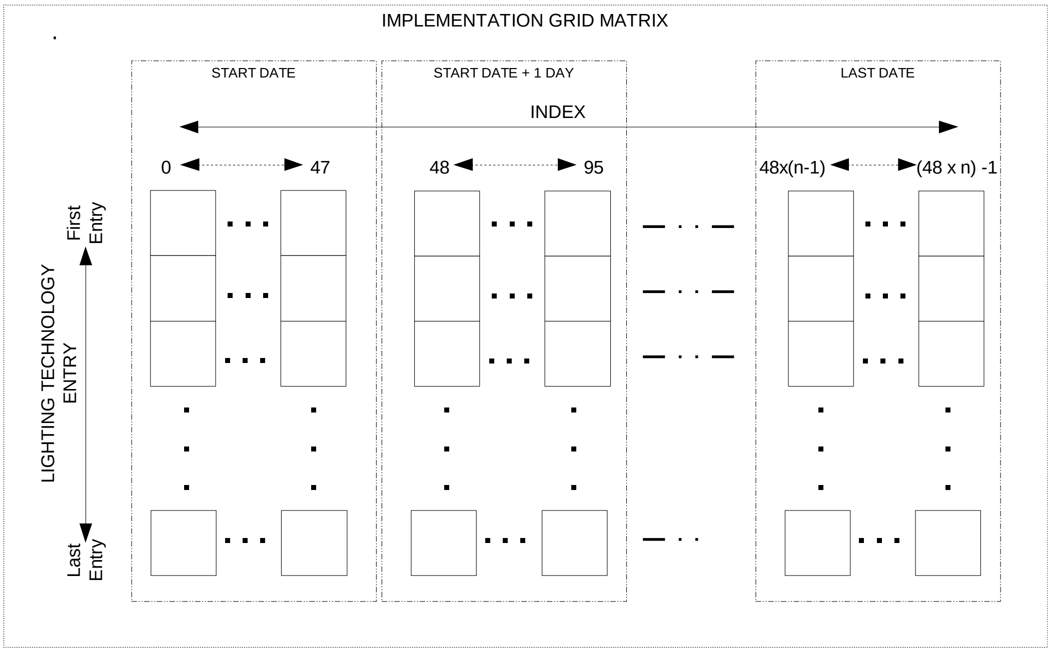

Figure 147: Illustration of the implementation grid assigned to each sectional area.

Once the user is satisfied that the data within the sectional area form is correct, and chooses to add the specific area to the project, the data in the implementation grid matrix is transferred to a similar grid matrix on the main form of the GUI. The grid matrix on the main form also contains descriptive information of all the user defined sectional areas.

5.3.3 Condonable days

Figure 148 illustrates how the GUI merges condonable days into the calculation process. The artificial-light usage profiles of condonable days and/or public holidays are added to the sectional area profile grid matrix as an extra row as illustrated in Figure 148. Thereafter the profile is used in calculating the active energy usage of the specific sectional area. The resulting active energy profile is then stored within the implementation grid matrix and then transferred to the main form of the GUI.

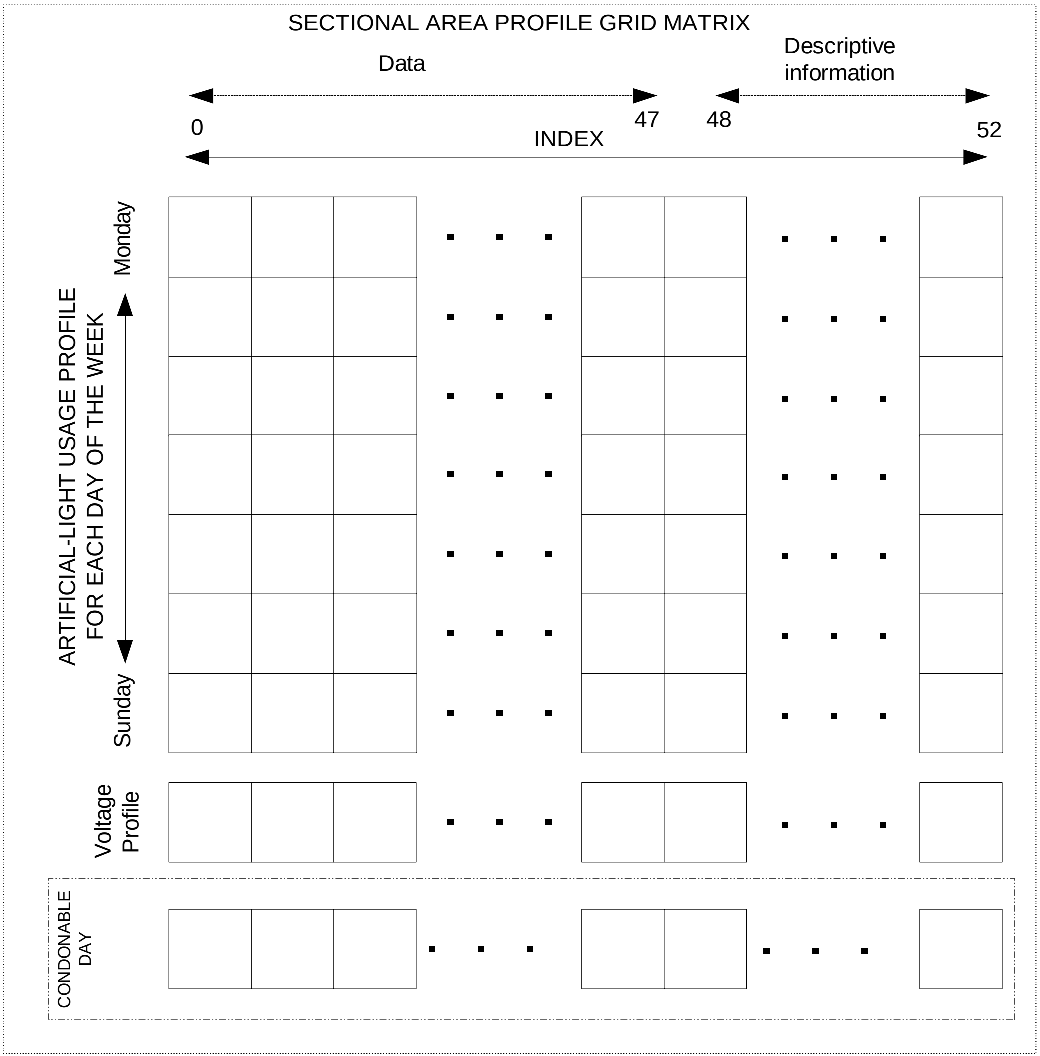

Figure 148: Illustration of where condonable days are inserted within the profile grid assigned to each sectional area.

5.4 GUI features

5.4.1 Overview

The main features that the GUI implements:

- Lighting technologies and their mathematical models can be created and stored.
- Voltage profiles and artificial-light usage profiles can be created and stored.
- Project cases can be saved and recalled.
- Active energy profiles can be exported to Microsoft Excel.
- Figures can be copied from the GUI to the clipboard.
- The database can be accessed and managed.

5.4.2 Saving and loading project cases

Project cases are stored as a Microsoft Excel file, by using a Borland Delphi Formula 1 workbook component. The files contain lighting technology information as well as references to voltage and artificial-light usage profiles that are available in the database tables. The text file also contains descriptive information about each case, along with all the necessary information to perform the active energy profile calculations, i.e. numbers and types of light fittings, sectional areas, etc. All information is distributed over three sheets of the Microsoft Excel workbook according to the following scheme:

- *Workbook Sheet 1:*
  - The project case name, period and the project boundary value.
  - Descriptions of all the relevant lighting technologies used in the project case.
  - The total number of light fittings of each type (pre- and post-implementation) used in the project case.
- *Workbook Sheet 2:*
  - Descriptions of all the sectional areas defined by the user
  - Descriptions and the database table references of all the voltage and light usage profiles associated with each sectional area entry.
- *Workbook Sheet 3:*
  - Numbers of the pre- and/or post-implementation lighting technologies associated with each sectional area.
  - Lighting technolgies' IDs relating to their position within the pre- and post-implementation lighting technology grids contained on the main form of the GUI.

Project cases are loaded in three phases corresponding to the three workbook sheets in which the information is stored. The three phases follow the procedure that a user would use to create a project case and can be summarized as follows:

- *Phase 1:*
  - The project case name as well as period and boundary values are retrieved from the stored file and inserted onto the main form of the GUI.
  - The pre-and/or post-implementation lighting technologies' descriptions are retrieved from the stored file, the database is then searched for those lighting technologies and if they are still contained within the database, it is inserted into either the pre-implementation or post-implementation lighting technology grid contained on the GUI's main form.
- *Phase 2:*

- The sectional areas' information is retrieved from the stored file and then inserted onto the main form of the GUI.
- The voltage and light usage profile references (names as well as periods in the case of custom profiles) associated with the sectional areas are retrieved from the stored file and inserted onto the main form of the GUI. This information is not visible to the user.

- *Phase 3:*
    - The numbers and types of light fittings for the pre- and/or post-implementation lighting technologies associated with the sectional areas are retrieved from the stored file and inserted onto the sectional areas form of the GUI.
    - The sectional areas grid on the main form of the GUI is then updated.
    - This process is repeated for each sectional area individually.

5.5 Conclusions

The LPST fulfils all of the GUI and database requirements proposed in section 5.1. It also successfully implements the functions prescribed by the methodology for assessing EE lighting projects, i.e. assigning profiles to groups/sectional areas, implementing the use of condonable days, etc.

6. Practical Evaluation of the Lighting Projects Software Tool

6.1 Introduction

In order to evaluate the performance of the LPST, it was used to conduct the performance assessment of a real energy-efficient lighting project, namely the case study of a DSM project implemented at a coal terminal.

The evaluation focussed on the following issues:

- Program functionality
- Practical usefullness and ease of application
- Identifying programming errors
- Determining the accuracy of the calculations

6.2 Overview of the DSM case study

The case study involved a DSM energy-efficient lighting intervention at a coal terminal, where the ESCO proposed to reduce the overall artificial-lighting load by 0.499 MW whilst maintaining pre-implementation service levels. The initiative involved the following interventions [23] :

- Replacing old fittings and energy-inefficient lamps with new fittings and energy-efficient lamps.
- Retrofitting energy-inefficient control gear by replacing it with energy-efficient Electronic Control Gear (ECG) and new lamps. The existing fittings remain intact.
- Replacing incandescent lamps with CFLs (the existing fittings and control gear remain the same)
- Replacing existing HID lamps with more efficient HID lamps (the existing fittings and control gear remain the same).
- Existing TFLs fittings is replaced or retrofitted with ECG.
- Existing bulkheads is replaced with similar fittings or TFLs.

The case study targets a single export coal terminal, which is situated at one of the world's deep sea ports. This coal terminal operates on a 24 hour basis. The areas of the site that are relevant to the DSM intervention have been divided into the following sections [23][24]:

- Administration/technical services.
- Radio tower.

- Carport/parking technical services.
- Tippler/ship loader workshop.
- Site cleaning workshop.
- Clinic and old training centre.
- Main administration building.
- Gatehouse.
- Canteen.
- All conveyors.
- All transfer towers.
- Dockside fencing lights.
- Ship loaders/wharf conveyors.
- Tipplers.
- All pole lights.
- Wharf transfer towers/buildings.
- Belt motors.
- Substations and transformer rooms.
- Stackers/reclaimers.
- NOSA offices.
- Training centre project.
- Yard machine workshop.
- Miscellaneous areas.

Conveyor motors and lighting forms a substantial part of the electrical load of the coal terminal. For the DSM intervention, however, only the lighting load rated at approximately 900 kW was targeted. The ESCO supplied the lighting load information, which was verified by the M&V team by means of a site survey that involved the verification of the numbers, types and power ratings of light fittings of randomly selected areas of the targeted load [[23], [24]].

Appendix C summarises the following details for lighting load at the targeted site:

- Pre-implementation and post-implementation lighting technologies that are relevant to the intervention, as supplied by the ESCO.
- Pre-implementation and post-implementation lighting technologies categorized according to the sectional areas identified in section 6.2 [24].

6.3 Impact assessment results

6.3.1 Implementation of the load characteristics

The ESCO used the following information for to the artificial-light usage profiles in their scoping calculations [[23][24]]:

- Most of the artificial-light load is operational 365 days a year
- 91.7 % of the artificial-light load operates 24 hours a day, 7 days a week
- 5.5 % of the artificial-light load operates 10 hours a day during day time, 6 days a week
- 2.8 % of the artificial-light load operates 10 hours a day during the night, 7 days a week

For the purposes of this case study using the software tool, the following pre-implementation load characteristics were adopted [24]:

- *Load rating:* Appendix C summarises the pre-implementation lighting load characteristics used in the assessment.
- *Voltage:* The voltage dependency of a lighting technology is not generally taken into consideration in energy-efficient lighting projects. For the case study, a fixed measured power consumption was used, and therefore the voltage dependency was not brought into consideration. As a result, no average voltage profile is required in the calculation. The LPST does however require a voltage profile, thus an arbitrary voltage profile of a constant nominal voltage, 230 V, is used [[23][24]].
- *Artificial Light Usage Profiles:* The load was subdivided as follows in order to assign artificial-light usage profiles to different sections of the load [24]:
    - Light Usage Profile 1 (LUP 1), based on office hours between 07h30 and 17h00.
    - Light Usage Profile 2 (LUP 2) based on night-time hours between 17h00 and 07h00. The lights on this profile are controlled by daylight switches and the operating hours are determined using sunrise and sunset times for the area in which the coal terminal is situated.
    - Light Usage Profile 3 (LUP 3) which operates 24 hours a day.

    Figure 149 to Figure 151 show the three artificial-light usage profiles used in the assesment.

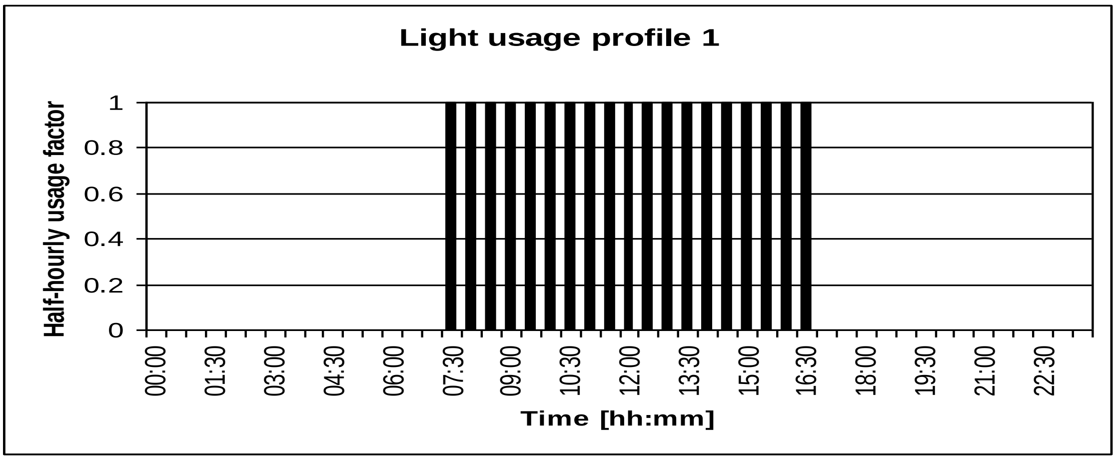

Figure 149: Artificial-light usage profile for daytime load [24].

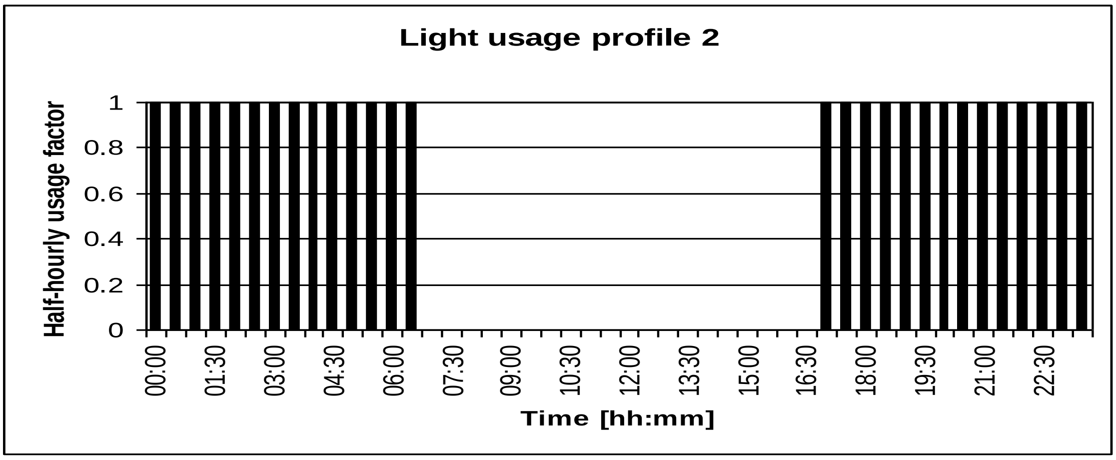

Figure 150: Artificial-light usage profile for the night-time load [24].

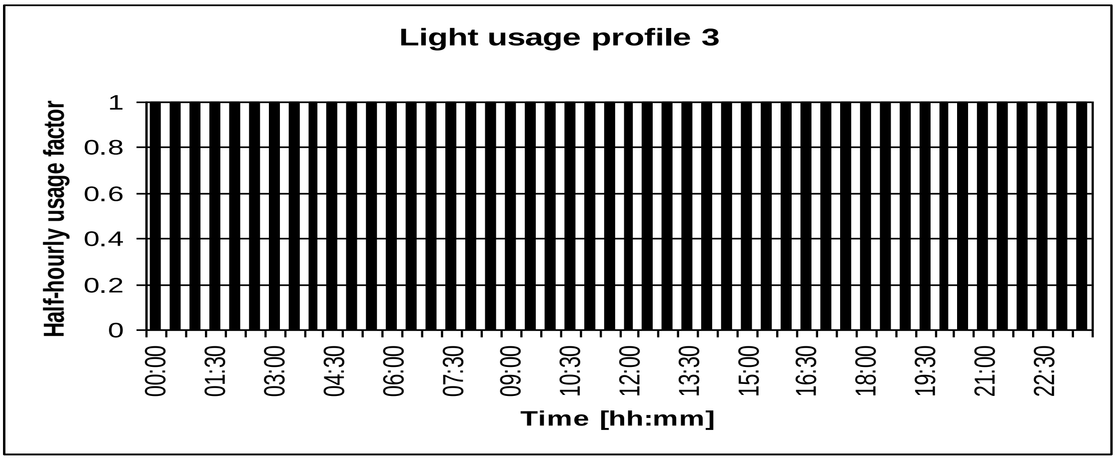

Figure 151: Artificial-light usage profile for the 24-hour load [24].

The areas associated with each of the LUPs are as follows [24]:

- *Light Usage Profile 1:*
    - Administration/technical services.

- Clinic and old training centre.
- Main administration building.
- NOSA offices.
- Training centre project.

- *Light Usage Profile 2:*
  - Carport/parking technical services.
  - 75 % of all conveyors.
  - 75 % of all transfer towers.
  - Dockside fencing lights.
  - All pole lights.
  - 75 % of all belt-drive areas.
- *Light Usage Profile 3:*
  - Radio tower.
  - Tippler/ship loading workshop.
  - Site cleaning workshop.
  - Gatehouse.
  - Canteen.
  - 25 % of all conveyors.
  - 25 % of all transfer towers.
  - Ship loaders/wharf conveyors.
  - Tipplers.
  - Wharf transfer towers/buildings.
  - 25 % of all belt-drive areas.
  - Substations and transformer rooms.
  - Stackers/reclaimers.
  - Yard machine workshop.
  - Miscellaneous areas containing industrial lighting accounting for approximately 1 % of the pre-implementation installed lighting load.

The following post-implementation load characteristics were adopted [24]:

- *Load rating:* Appendix C summarises the post-implementation lighting load characteristics used in the assessment.
- *Voltage:* A constant supply voltage of 230 V is assumed.

- *Artificial Light Usage Profiles:* The load is subdivided in the same manner as the pre-implementation load.

Figure 152 to Figure 154 show the pre-implementation an expected post-implementation average light load profiles for a typical weekday, Saturday and Sunday, respectivelyThese results are based on calculations made by the M&V team.

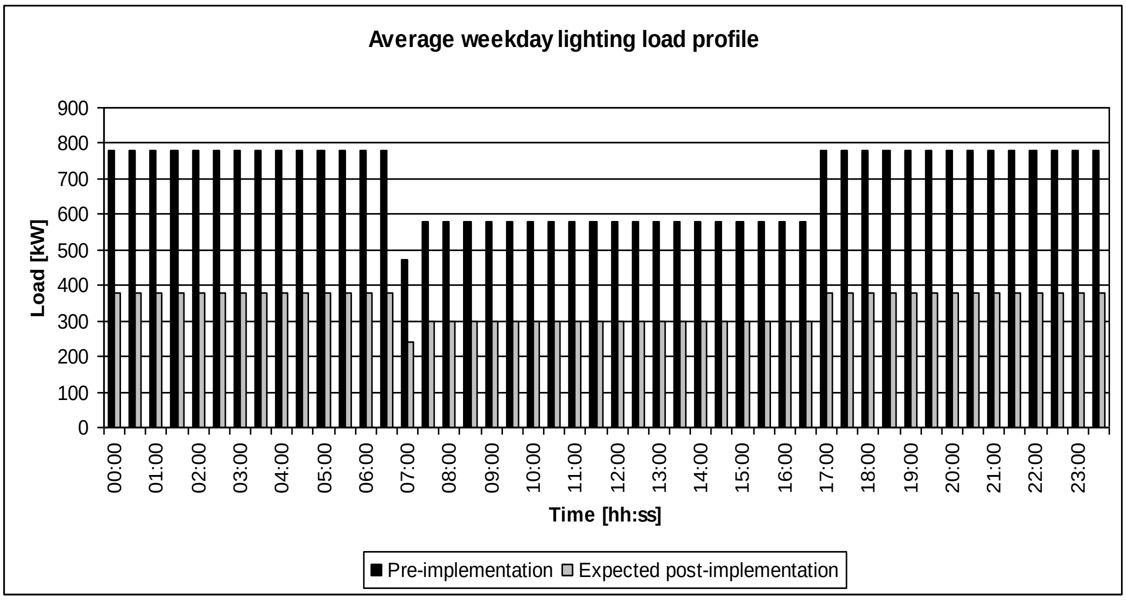

Figure 152: Pre-implementation and expected post-implementation weekday light load profiles [24].

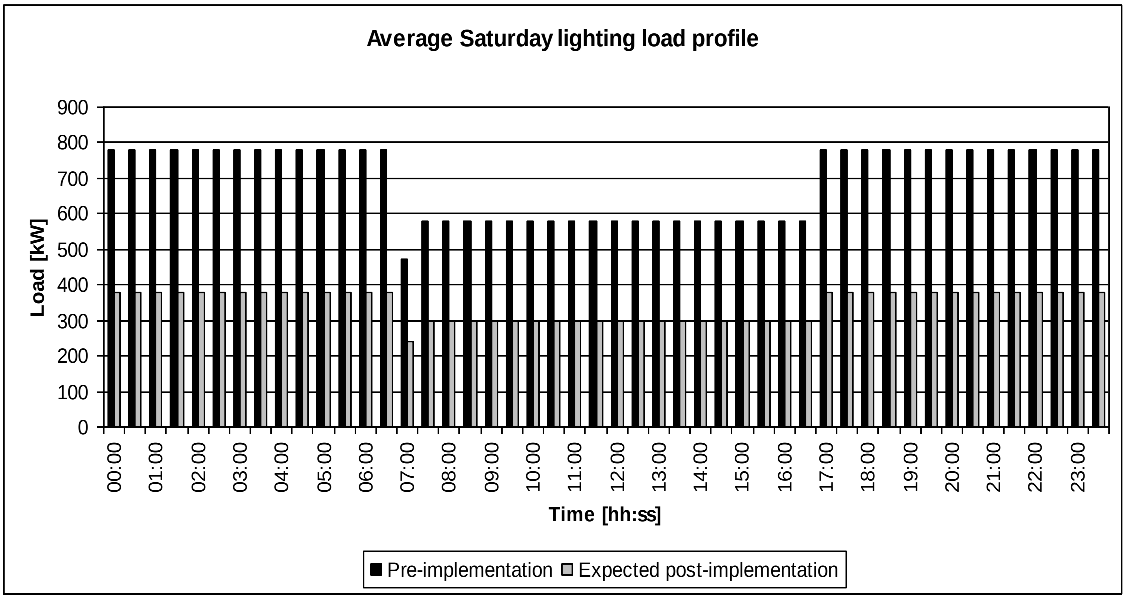

Figure 153: Pre-implementation and expected post-implementation Saturday light load profiles [24].

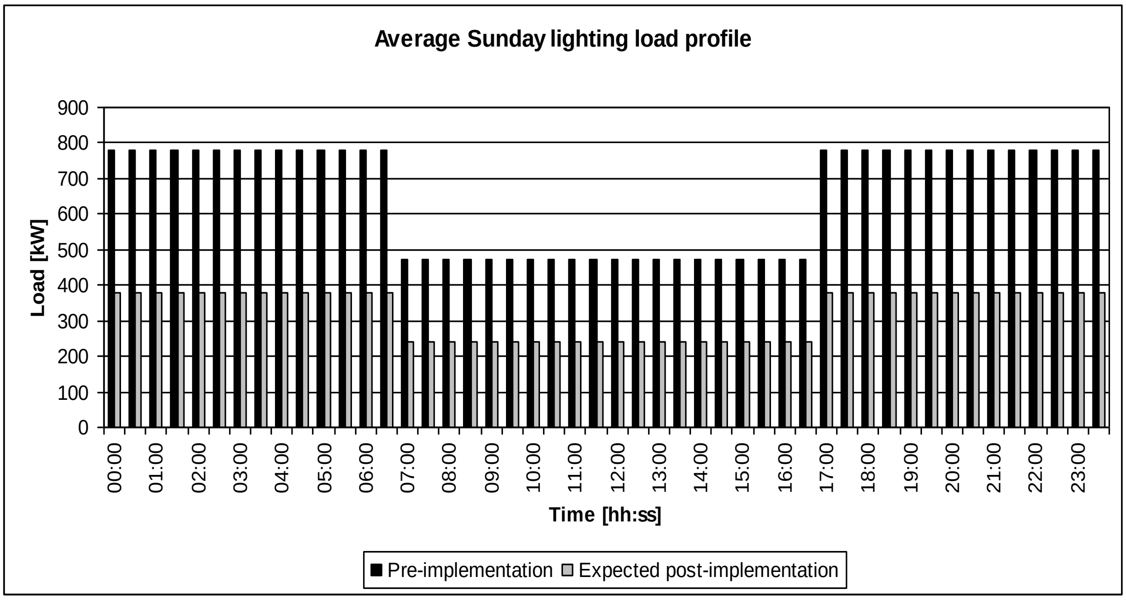

Figure 154: Pre-implementation and expected post-implementation Sunday light load profiles [24].

General practice for determining the half-hourly active energy consumption of an energy-efficient lighting project is to use the manufacturer's power rating for a specific lighting technology in the calculation. However, the manufacturer's power rating is usually relative to a nominal voltage. This does not take into consideration any voltage dependency that the specific lighting technology might have. In the case study however, the ESCO uses measured power values in the calculation of the half-hourly active energy consumption. This is a more realistic and practical approach, but the measurements are still only taken at one specific voltage and does not account for the power consumption at other voltage levels. However, this measurement is utilized in the official M&V of the project and is therefore used in the LPST to determine the program's accuracy relative to the official reports. The mathematical model in this case, is a fixed measured value [23][24].

6.3.2 Results obtained with LPST

Figure 155 shows the resultant 7 day active energy consumption profile for both the pre-implementation and post-implementation stages along with the savings as calculated by the LPST.

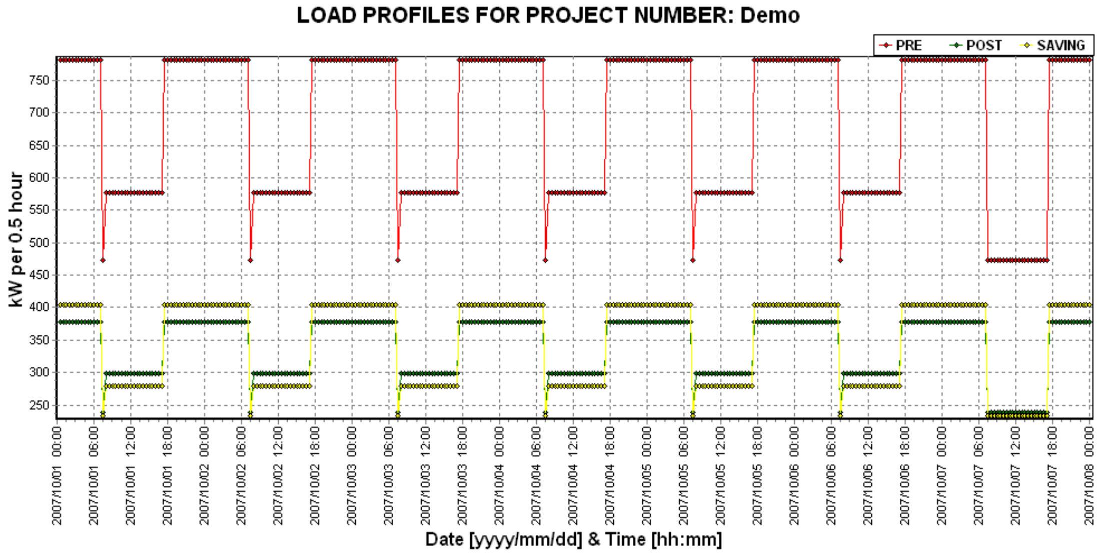

Figure 155: Pre-implementation and post-implementation active energy consumption profile delivered by the LPST.

Figure 156 to Figure 158 show the pre-implementation and post-implementation average light load profiles for a typical weekday, Saturday and Sunday, respectively. These figures also show the savings attained.

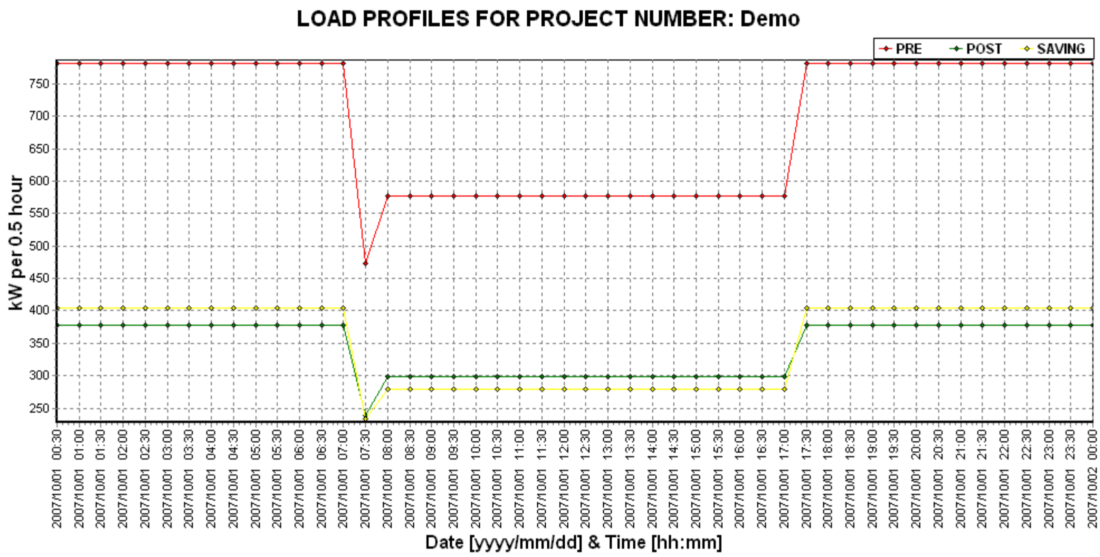

Figure 156: Pre-implementation and post-implementation average weekday light load profiles as well as the savings calculated.

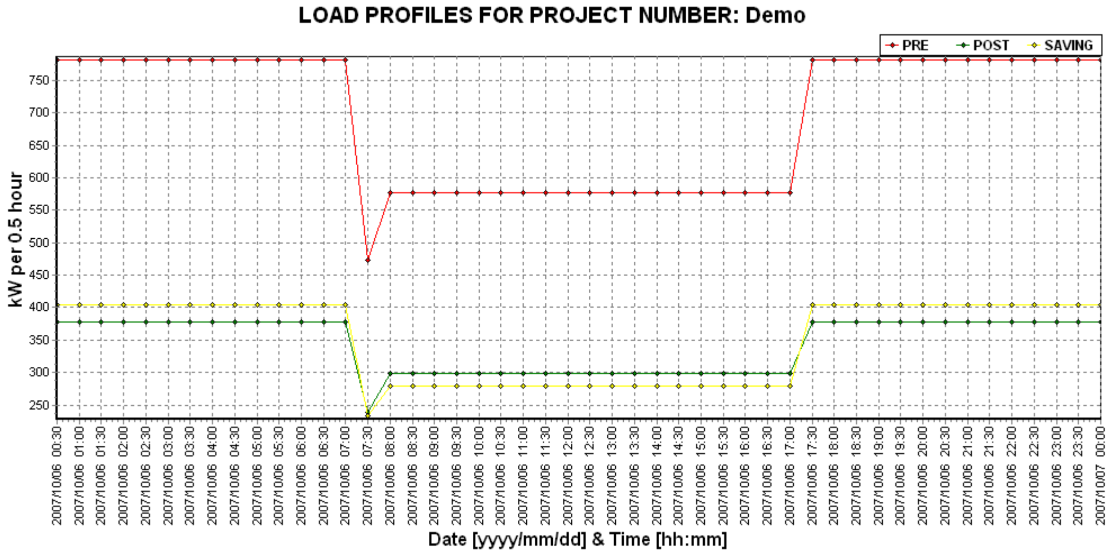

Figure 157: Pre-implementation and post-implementation Saturday light load profiles as well as the savings calculated.

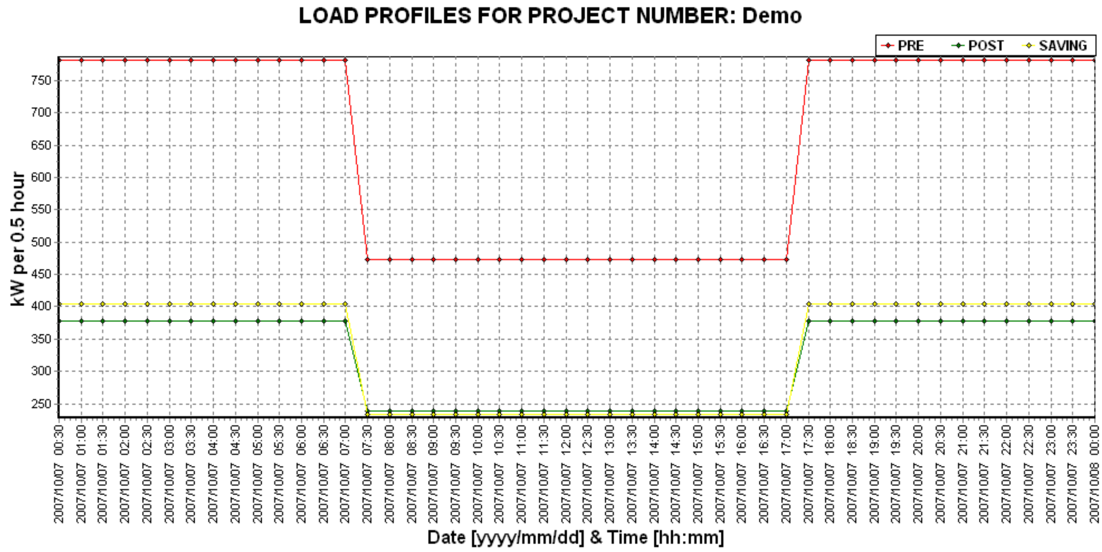

Figure 158: Pre-implementation and post-implementation average Sunday light load profiles as well as the savings calculated.

The results shown in Figure 156 to Figure 158 correlates accurately with results shown in Figure 152 to Figure 154.

6.4 Conclusions

The functions utilised in the implementation of this case study yielded no visible programming errors. The results given in section 6.3.2 show that the calculations implemented by the LPST yield accurate results compared to the results contained in the official M&V documentation of this project [24]. The practical usefullness and application of the LPST are heavily dependent on the availability of the required inputs to the LPST, i.e. mathematical models, profiles, etc. If these inputs are available the LPST represents a time-saving and accurate tool for determining active energy impacts.

7. Conclusions and Recommendations

7.1 Conclusions

7.1.1 Power consumption characteristics of typical lighting technologies

The lighting technologies investigated in this report exhibit significant deviation of power consumption from the respective rated power for the voltage range tested. Thus, provision for voltage dependency could have significant impacts on energy savings calculations. Table 27 illustrates the average power consumption deviation, for each lighting technology represented, at 207 V, 230 V and 253 V.

Table 27: Averages of power deviations at 207 V, 230 V and 253 V for the lighting technologies tested.

Lighting technology	% of rated power		
	at 207 V	At 230 V	at 253 V
ILs	81.65	95.49	110.43
CFLs	81.56	90.09	102.52
TFLs (magnetic ballast)	92.5	118.36	145.18
TFLs (electronic ballast)	86.73	96.56	107.16
HIDLs	71.58	90.33	111

Creating and utilising voltage-dependent active power consumption models such as determined in chapter 3 can significantly increase the accuracy of energy savings calculations. The voltage-dependent behaviour of the various lighting technologies can be summarised as follows:

- The RMS current consumption measurements for the ILs, as well as the lighting technologies utilising magnetic ballasts, display linear characteristics.
- TFLs with electronic ballasts draw an approximately constant RMS current irrespective of voltage level.
- CFLs show an inconsistent RMS current usage trend.

The apparent power measurements, for all the lighting technologies, show an increasing linear trend for an increase in supply voltage, which is to be expected as none of the lighting technologies draw less RMS current as the supply voltage increases.

7.1.2 Supply current harmonics and neutral currents

Table 28 summarises the approximate THD range and the three-phase neutral current as a percentage of the RMS phase current for each of the technologies tested.

Table 28: Summary of the THD and neutral current loading for the lighting technologies presented.

Lighting technology	THD range [%]	Neutral current [% of -phase current]
ILs	0.11 % to 0.18 %	Less than 4%
CFLs	110 % to over 250 %	Exceeds 170%
TFLs (magnetic ballast)	10 % to 22 %	Exceeds 50 %
TFLs (electronic ballast)	0.5 % to 2.5 %	25 %
HIDLs	2.5 % to 7 %	41 %

ILs and TFLs with electronic ballasts exhibit very low degrees of supply current distortion, while TFLs with magnetic ballasts and HIDLs exhibit moderate to low degrees of supply current distortion. CFLs exhibit very high degrees of supply current distortion. This gives rise to additional heat losses in the supply network, especially in distribution transformers [16]. If the CFL load forms a substantial amount of the overall load, it could lead to voltage distortion at the point of common coupling [17]. A substantial CFL load could also affect the power factor of the system [18].

The neutral current load characteristics for the various technologies can be summarised as follows:

- The measured results for three-phase ILs loads show that the ILs give rise to an insignificant amount of neutral current loading.
- The measured results for three-phase TFLs with magnetic ballasts show a moderate amount of neutral current loading.
- The measured results for three-phase TFL with electronic ballasts show moderate to low neutral current loading.
- The measured results for three-phase HIDLs with magnetic ballasts show that the HIDLs give rise to moderate neutral current loading.
- The measured results for three-phase CFL loads show that the CFLs give rise to high neutral current loading. This is a potential cause for concern, especially for underrated networks.

The practical implications of the increased neutral current loads are increased voltage distortion at the consumer supply points, overheating of neutral conductors and connections, shift of the neutral voltage with respect to earth potential (with possible safety implications) and interference with protection schemes [19]. The severity of these effects is dependent on the relative CFL load rating, actual network ratings and network operating conditions.

7.1.3 Profile gathering

Given the correct equipment and the correct application thereof, obtaining accurate voltage profiles and artificial-light usage profiles can be gathered. A certain amount of post-processing is required. When using state change loggers, the deployment of the loggers might need to be customized to the specific project site. In the case off the Hobo® u9-002 light on/off data logger, minimizing direct exposure to natural light is a necessity.

7.1.4 Software program

The LPST satifies all of the GUI and database functions as proposed in section 5.1. It also successfully implements the methodology for assessing the impacts of EE lighting projects, i.e. assigning profiles to groups/sectional areas, implementing the use of condonable days, etc.

The implementation of the case study (see section 6) yielded no visible programming errors. The results delivered by the LPST are accurate relative to the results contained in the official M&V documentation of this project [24]. The LPST is highly useful in determining project savings.

7.2 Recommendations

Further research should be done on the effect of ageing, i.e. daily use over an extended period of time, on the power consumption of the lighting technologies. If ageing has a significant affect on the power consumption, it should be incorporated into the LPST.

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Appendix A Measurement data

A.1 Measurement results for Incandescent Lamps

Figure 159 to Figure 164 show the supply current as a function of the supply voltage for each of the samples (S_1, S_2, S_3) tested for the IL types listed in Table 3. The base value for the current is determined by

$$I_{base} = \frac{P_{rated}}{V_{nom}} \qquad [B.1\text{-}1]$$

Figure 165 to Figure 170 show the active power consumption as a function of supply voltage for each of the samples tested for the IL types listed in Table 3. The base value for the active power is the rated power of the IL.

Figure 171 to Figure 176 show the reactive power consumption as a function of supply voltage for each of the samples tested for the IL types listed in Table 3. The base value for the reactive power is the rated power of the IL.

Figure 177 to Figure 182 show the apparent power consumption as a function of supply voltage for each of the samples tested for the IL types listed in Table 3. The base value for the apparent power is the rated power of the IL.

Figure 183 to Figure 188 show the power factor as a function of supply voltage for each of the samples tested for the IL types listed in Table 3.

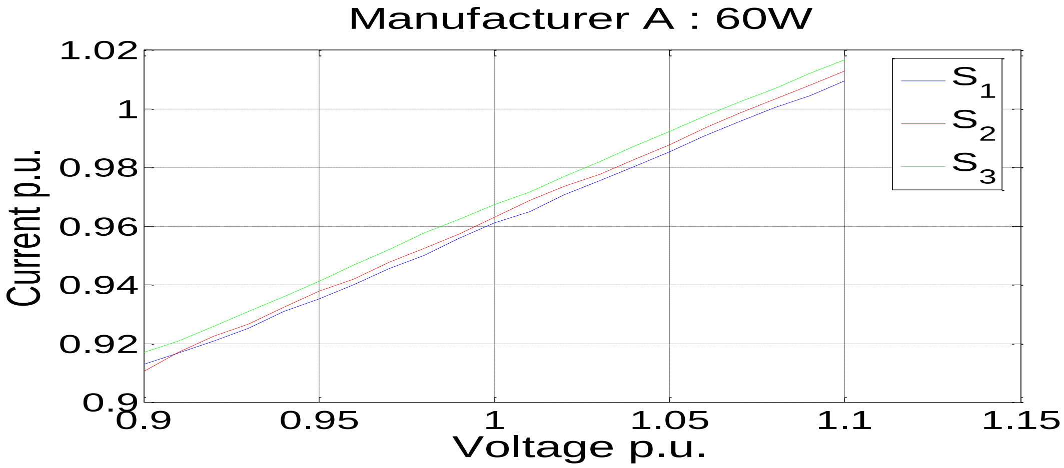

Figure 159: RMS supply current versus RMS supply voltage for the three 60 W IL samples from manufacturer A.

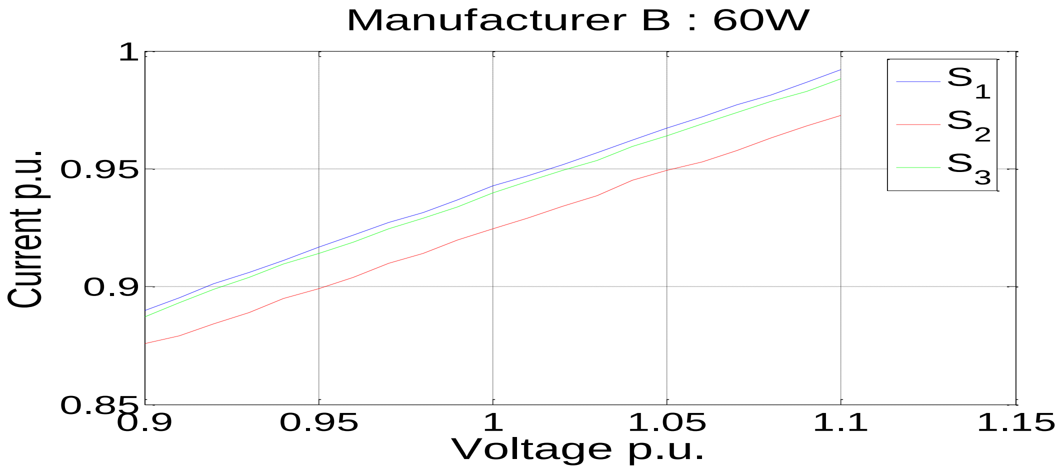

Figure 160: RMS supply current versus RMS supply voltage for the three 60 W IL samples from manufacturer B.

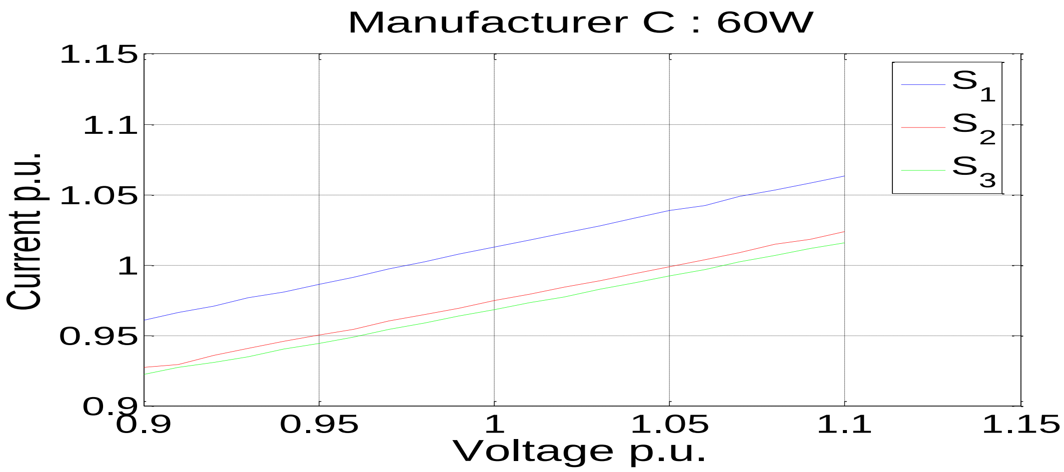

Figure 161: RMS supply current versus RMS supply voltage for the three 60 W IL samples from manufacturer C.

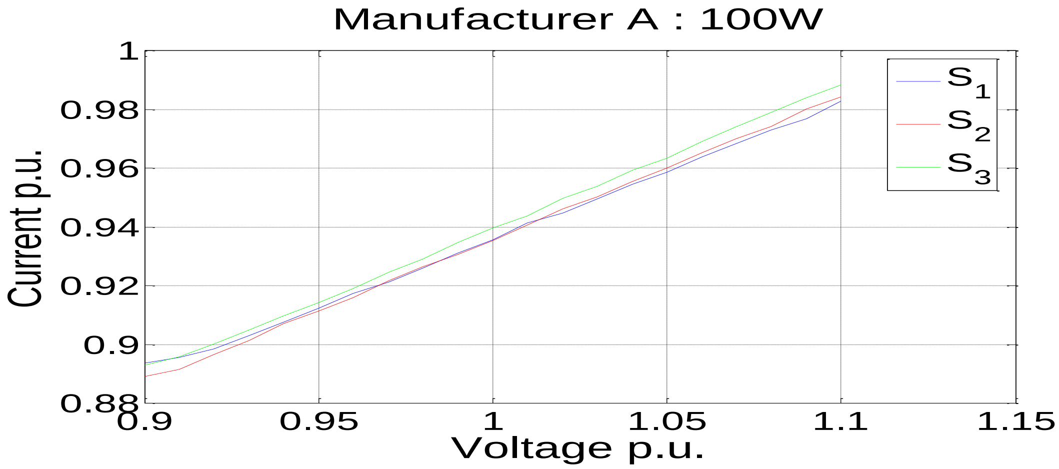

Figure 162: RMS supply current versus RMS supply voltage for the three 100 W IL samples from manufacturer A.

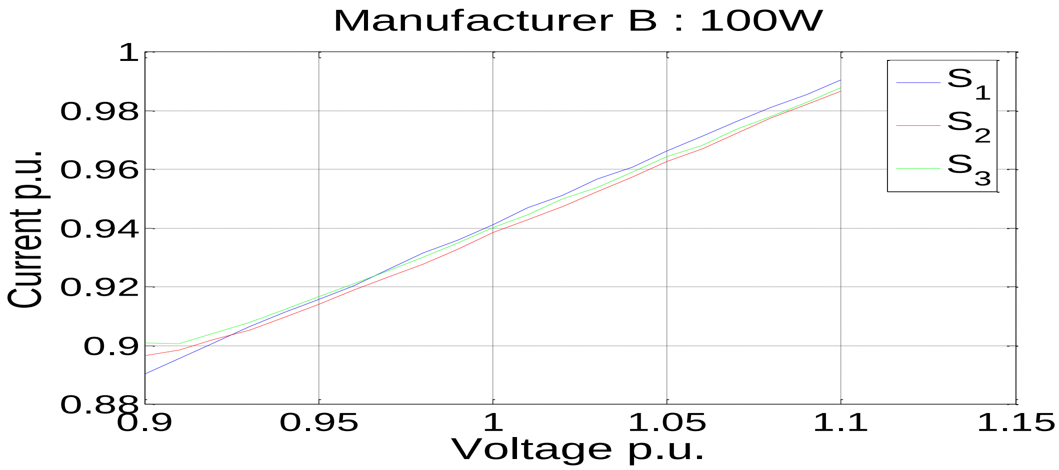

Figure 163: RMS supply current versus RMS supply voltage for the three 100 W IL samples from manufacturer B.

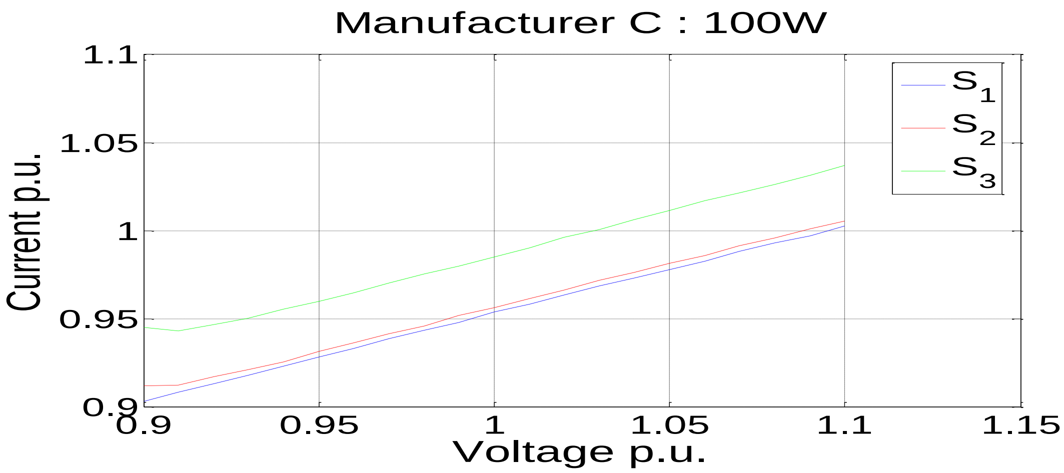

Figure 164: RMS supply current versus RMS supply voltage for the three 100 W IL samples from manufacturer C.

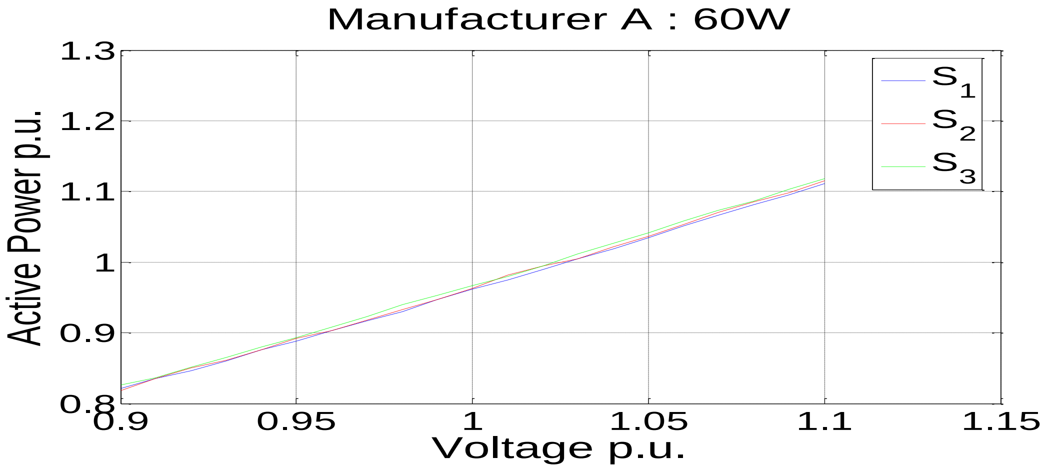

Figure 165: Active power versus RMS supply voltage for the three 60 W IL samples from manufacturer A.

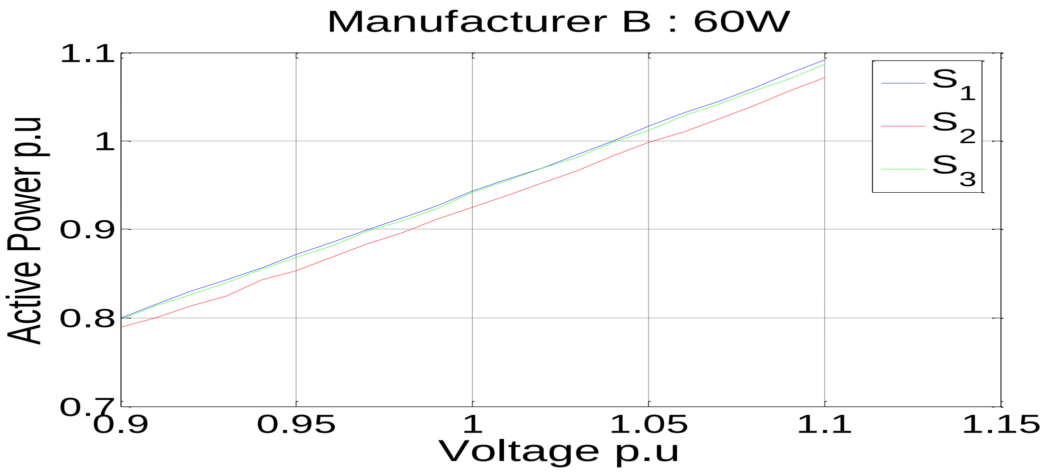

Figure 166: Active power versus RMS supply voltage for the three 60 W IL samples from manufacturer B.

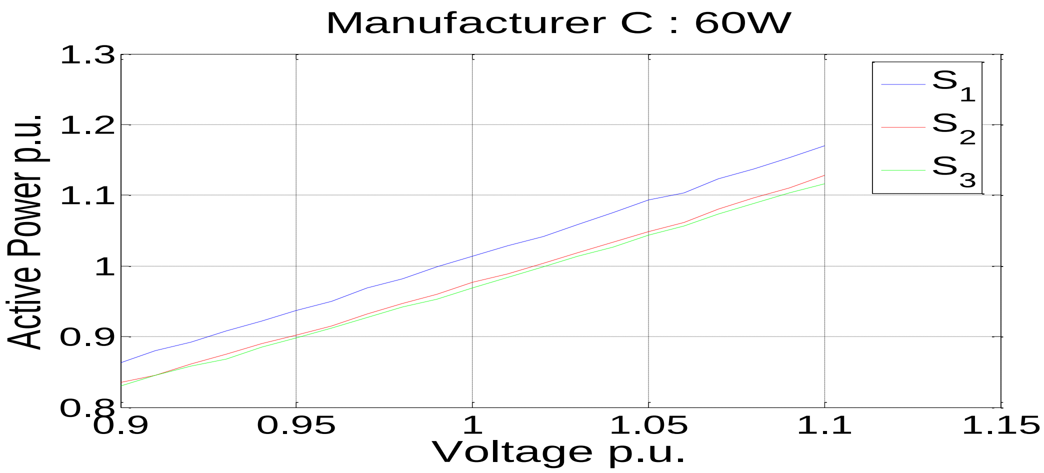

Figure 167: Active power versus RMS supply voltage for the three 60 W IL samples from manufacturer C.

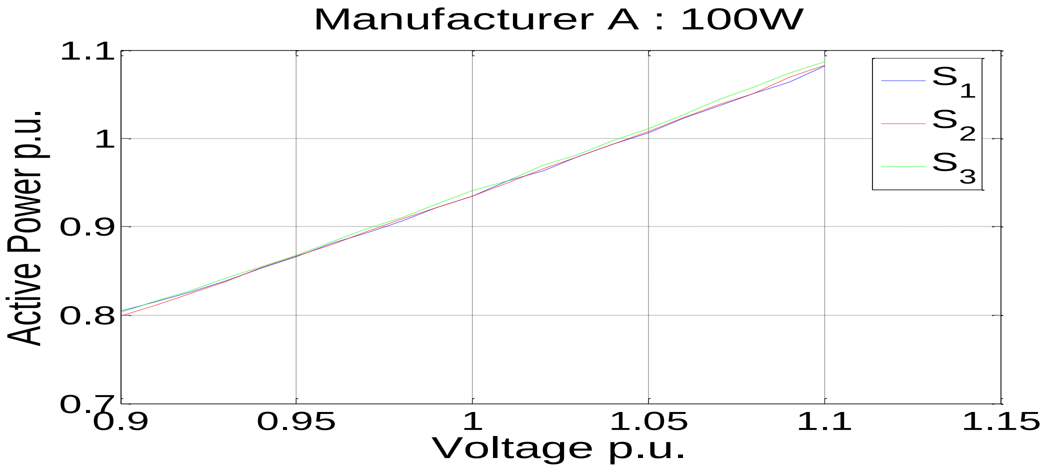

Figure 168: Active power versus RMS supply voltage for the three 100 W IL samples from manufacturer A.

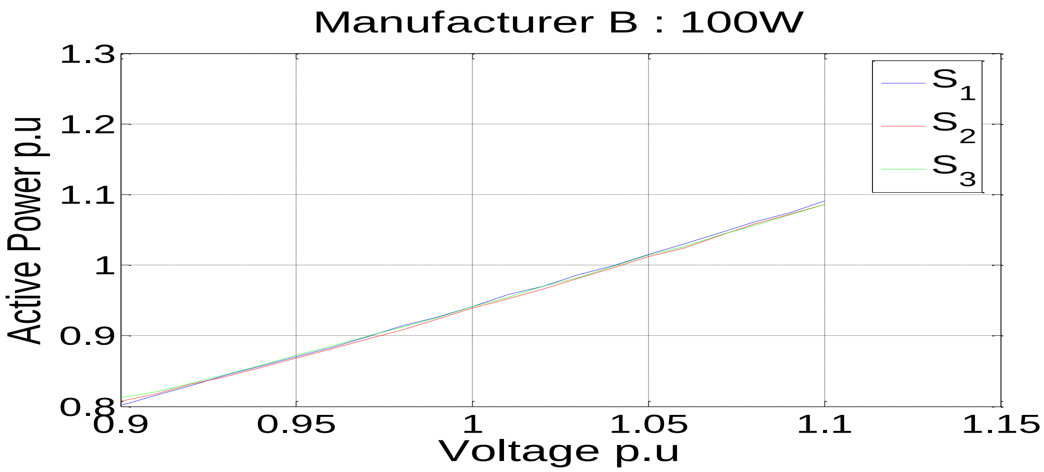

Figure 169: Active power versus RMS supply voltage for the three 100 W IL samples from manufacturer B.

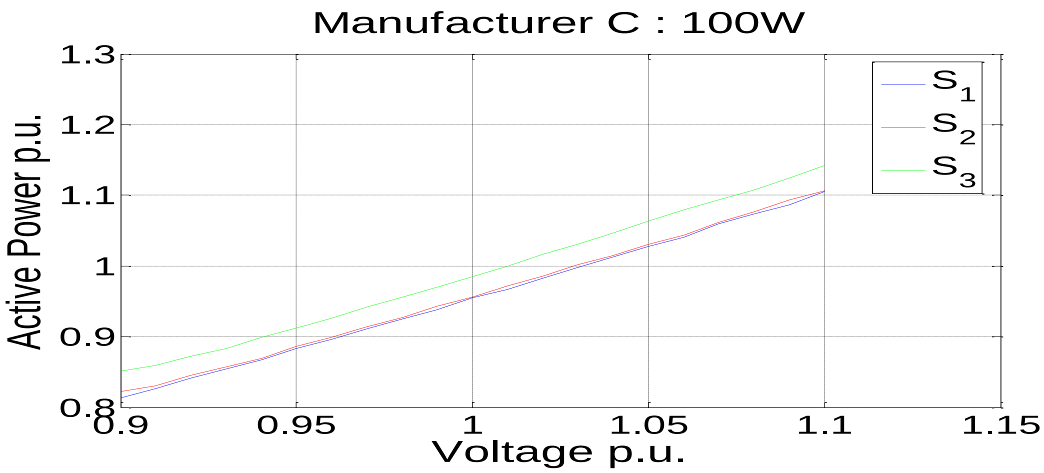

Figure 170: Active power versus RMS supply voltage for the three 100 W IL samples from manufacturer C.

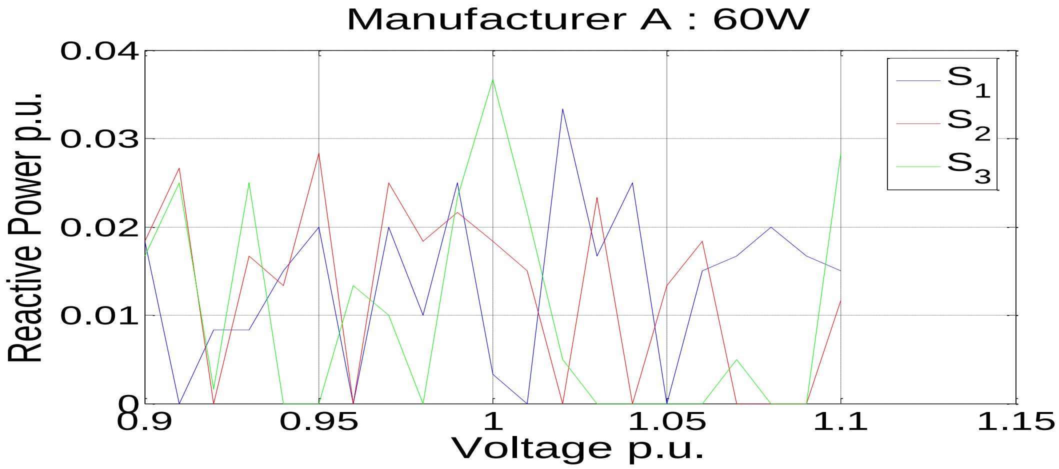

Figure 171: Reactive power versus RMS supply voltage for the three 60 W IL samples from manufacturer A.

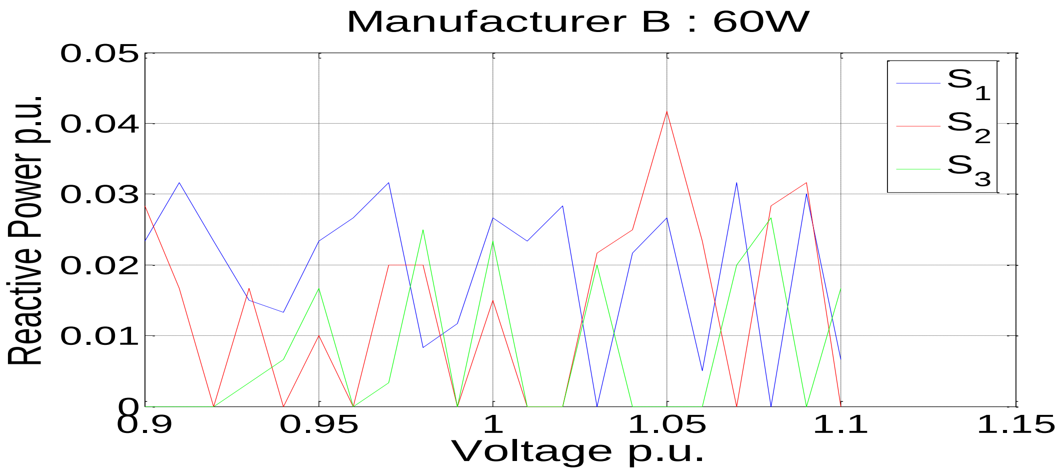

Figure 172: Reactive power versus RMS supply voltage for the three 60 W IL samples from manufacturer B.

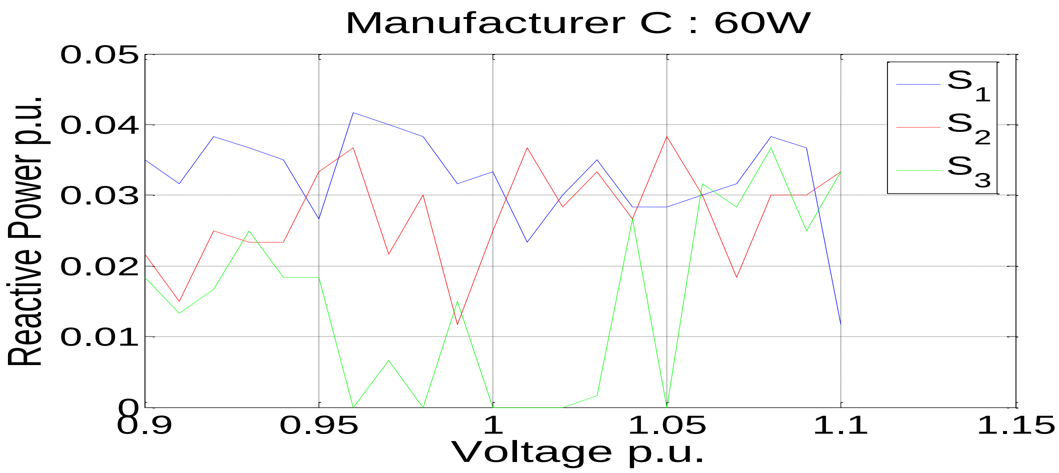

Figure 173: Reactive power versus RMS supply voltage for the three 60 W IL samples from manufacturer C.

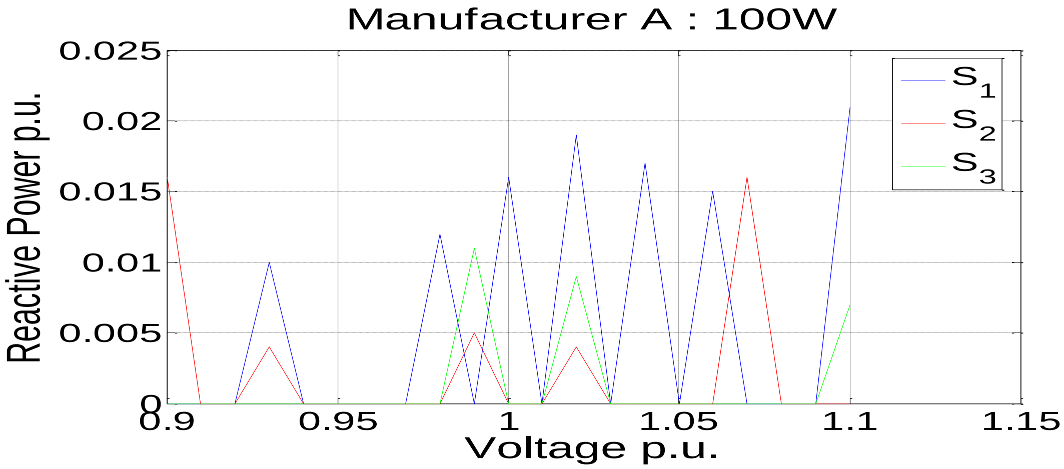

Figure 174: Reactive power versus RMS supply voltage for the three 100 W IL samples from manufacturer A.

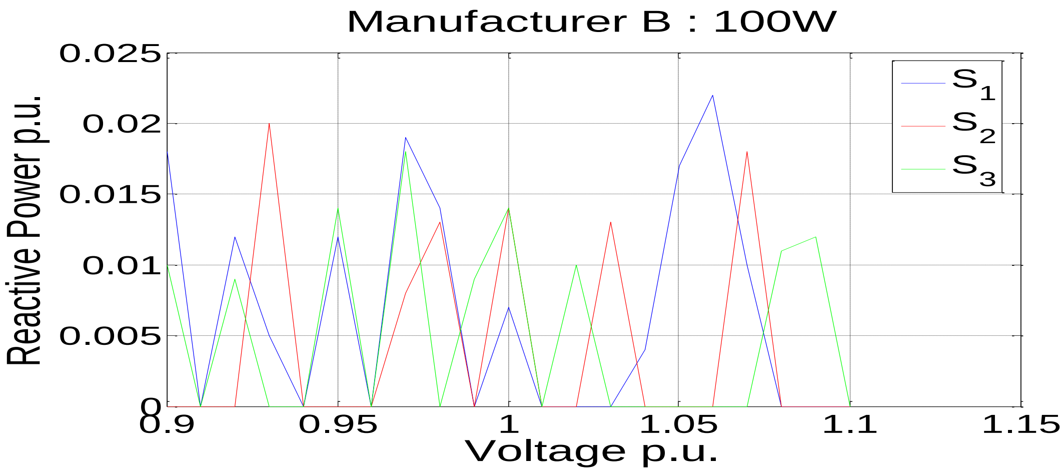

Figure 175: Reactive power versus RMS supply voltage for the three 100 W IL samples from manufacturer B.

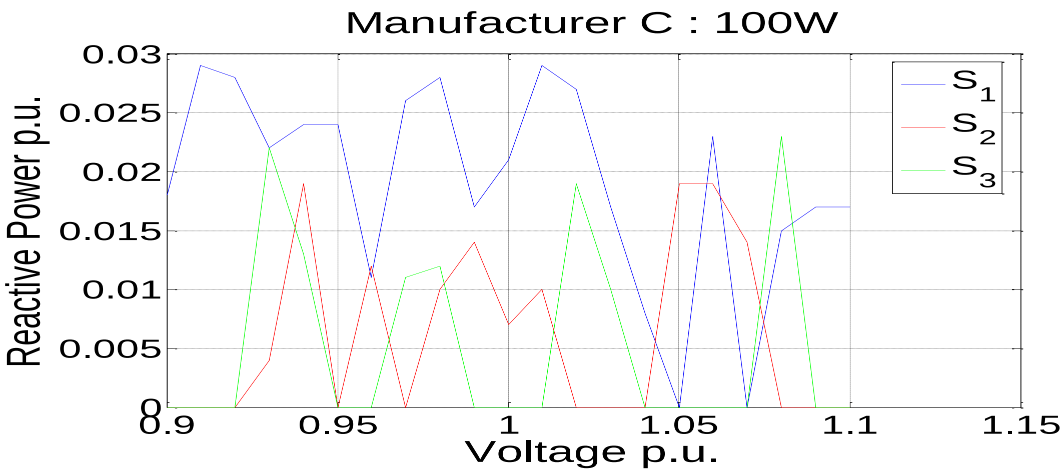

Figure 176: Reactive power versus RMS supply voltage for the three 100 W IL samples from manufacturer C.

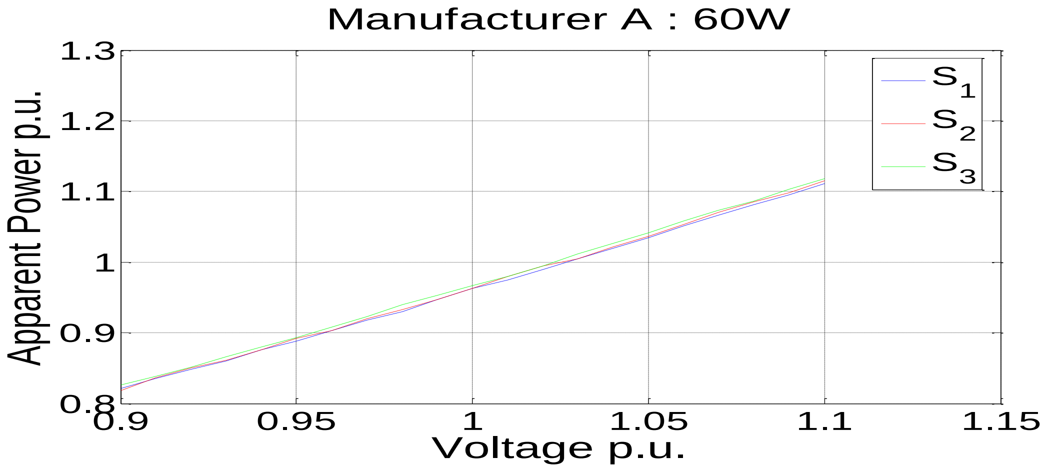

Figure 177: Apparent power versus RMS supply voltage for the three 60 W IL samples from manufacturer A.

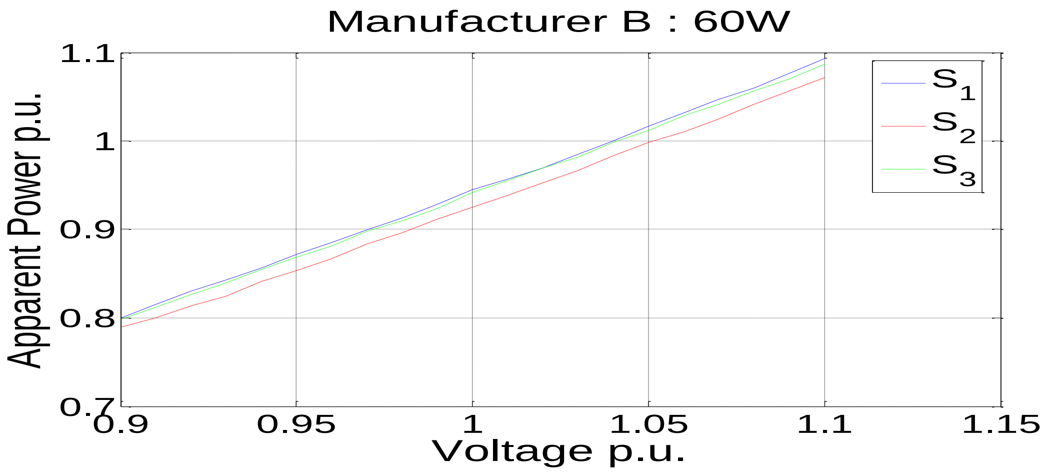

Figure 178: Apparent power versus RMS supply voltage for the three 60 W IL samples from manufacturer B.

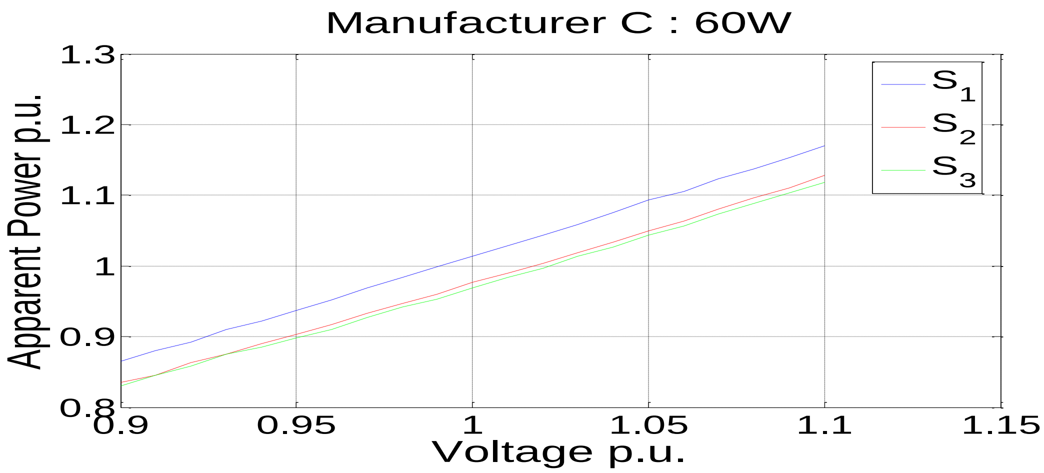

Figure 179: Apparent power versus RMS supply voltage for the three 60 W IL samples from manufacturer C.

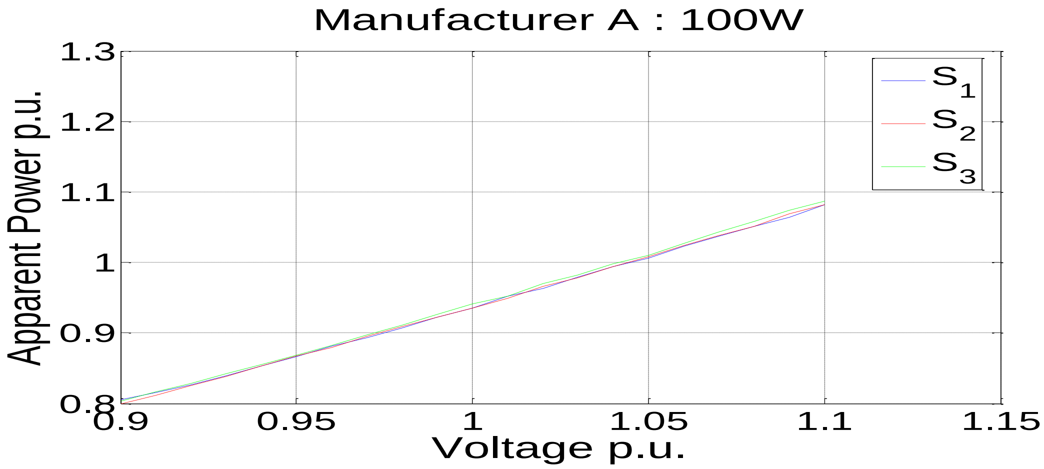

Figure 180: Apparent power versus RMS supply voltage for the three 100 W IL samples from manufacturer A.

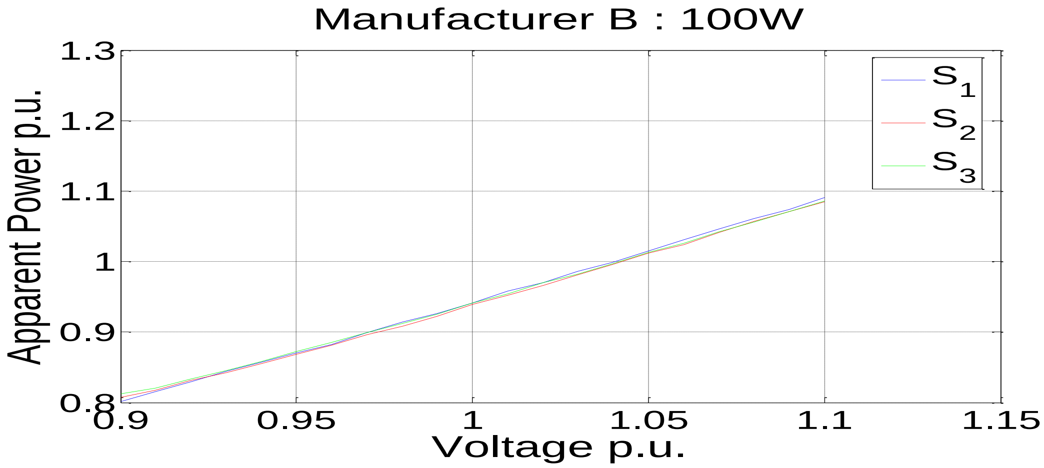

Figure 181: Apparent power versus RMS supply voltage for the three 100 W IL samples from manufacturer B.

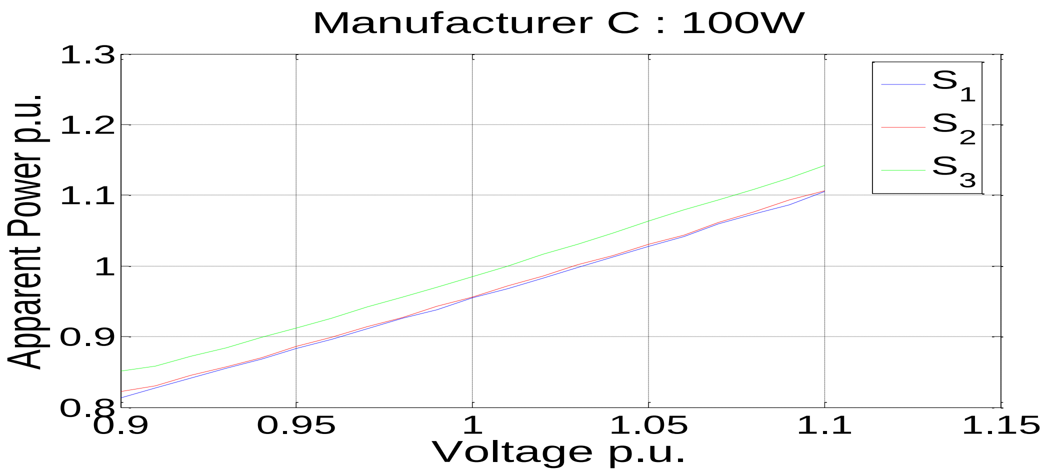

Figure 182: Apparent power versus RMS supply voltage for the three 100 W IL samples from manufacturer C.

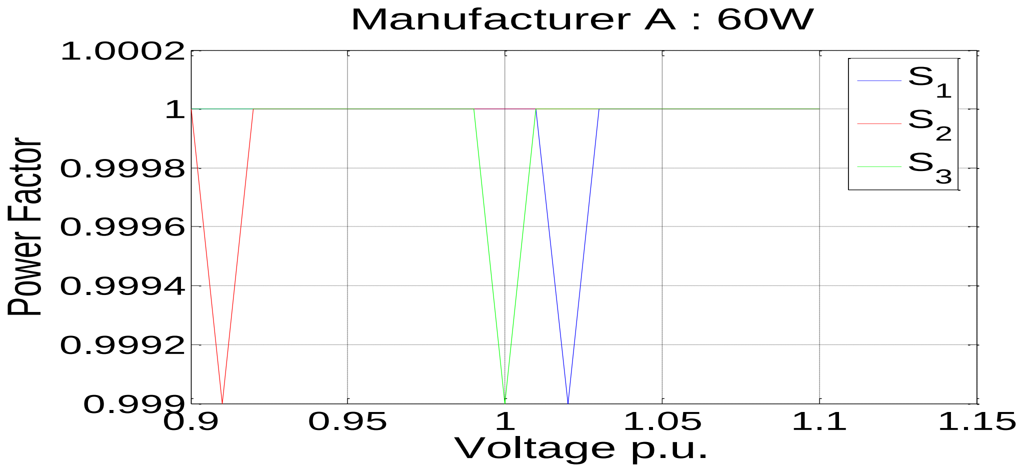

Figure 183: Power factor versus RMS supply voltage for the three 60 W IL samples from manufacturer A.

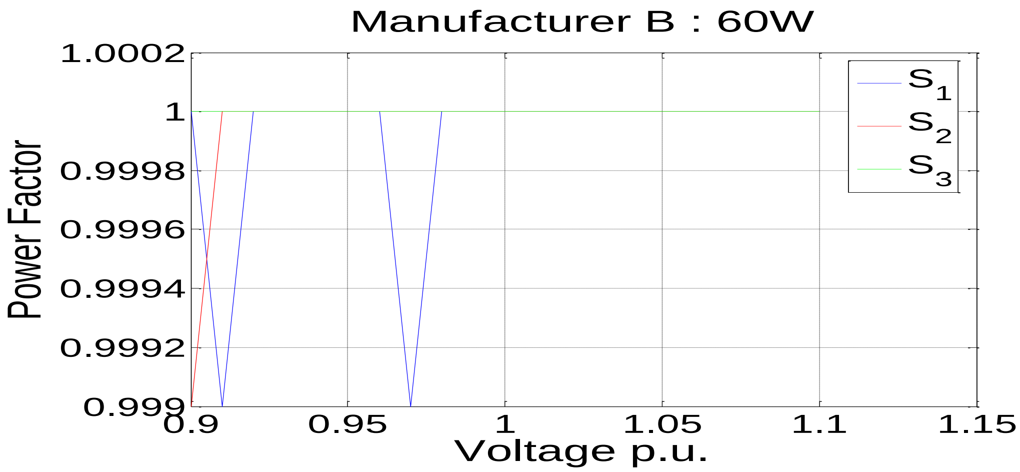

Figure 184: Power factor versus RMS supply voltage for the three 60 W IL samples from manufacturer B.

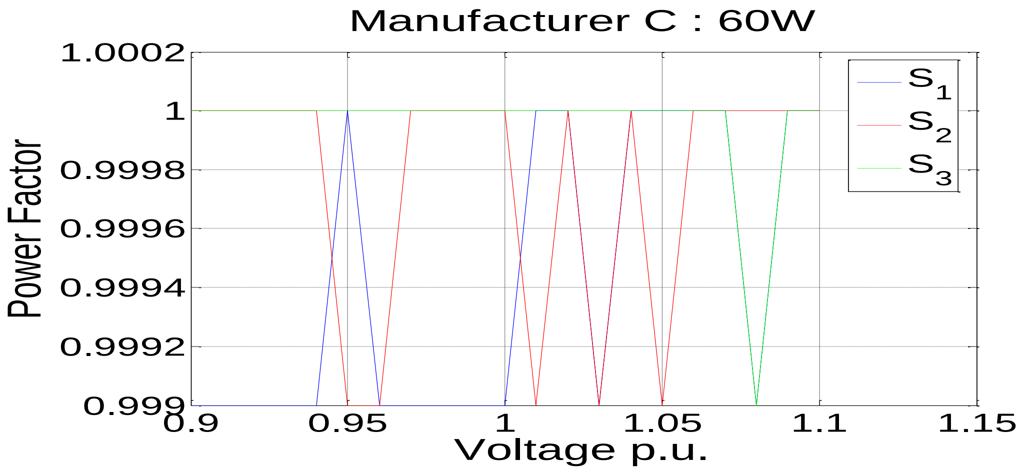

Figure 185: Power factor versus RMS supply voltage for the three 60 W IL samples from manufacturer C.

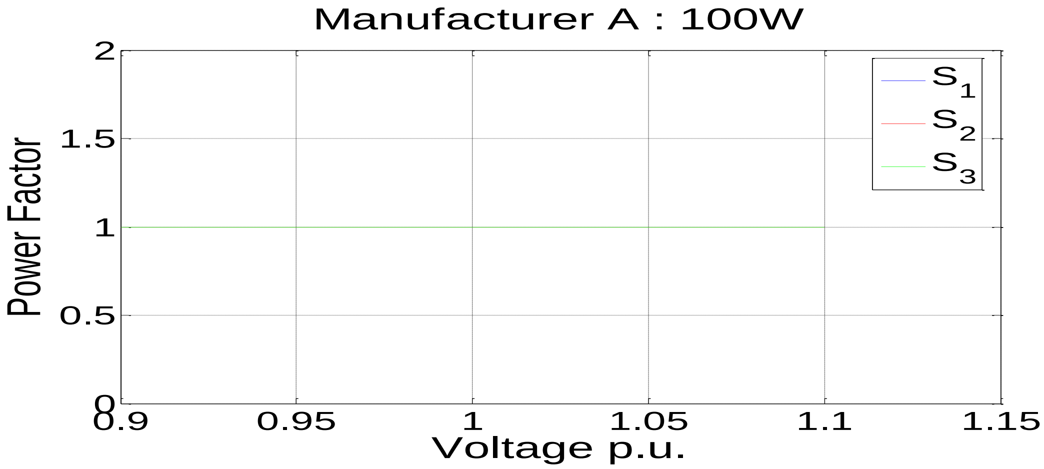

Figure 186: Power factor versus RMS supply voltage for the three 100 W IL samples from manufacturer A.

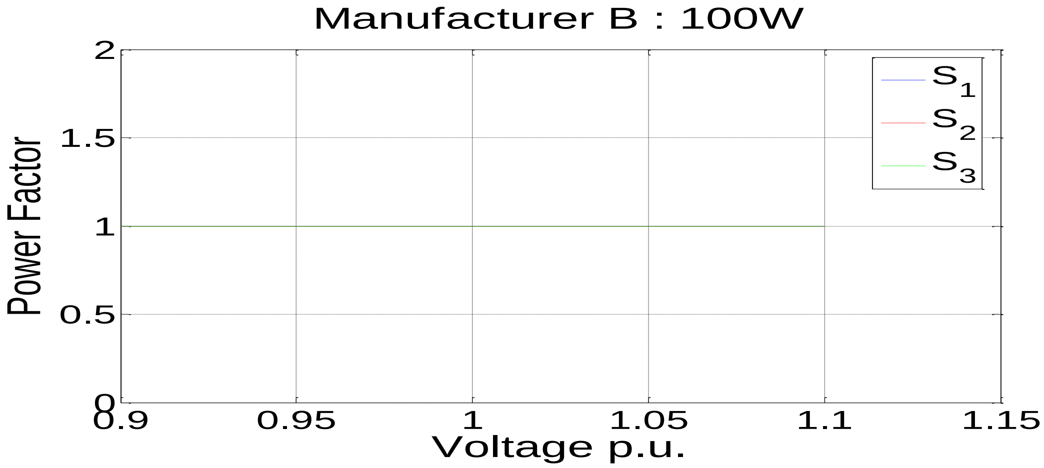

Figure 187: Power factor versus RMS supply voltage for the three 100 W IL samples from manufacturer B.

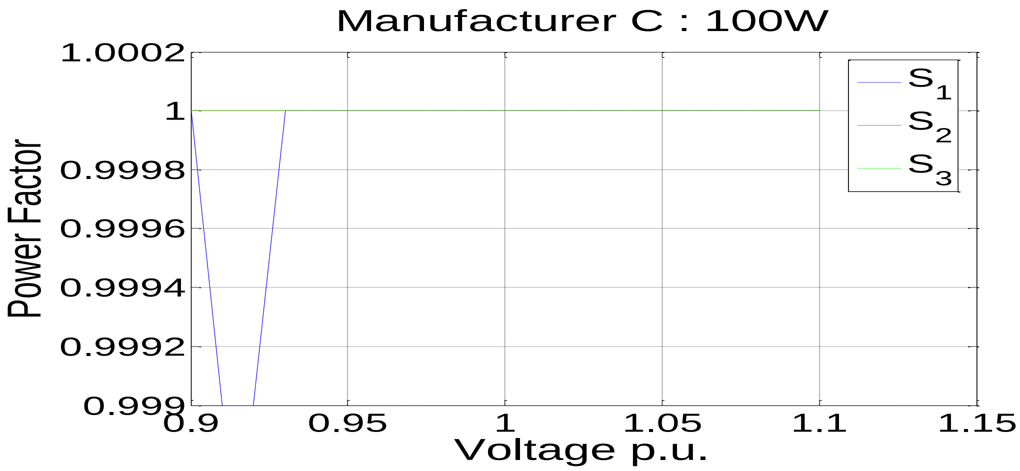

Figure 188: Power factor versus RMS supply voltage for the three 100 W IL samples from manufacturer C.

A.2 Measurement results for Compact Fluorescent Lamps

Figure 189 to Figure 194 show the supply current as a function of the supply voltage for each of the samples (S_1, S_2, S_3) tested for the CFL types listed in Table 7. The base value for the current is determined by equation B.1-1.

Figure 195 to Figure 200 show the active power consumption as a function of supply voltage for each of the samples tested for the CFL types listed in Table 7. The base value for the active power is the rated power of the CFL.

Figure 201 to Figure 206 show the reactive power consumption as a function of supply voltage for each of the samples tested for the CFL types listed in Table 7. The base value for the reactive power is the rated power of the CFL.

Figure 207 to Figure 212 shows the apparent power consumption as a function of supply voltage for each of the samples tested for the CFL types listed in Table 7. The base value for the apparent power is the rated power of the CFL.

Figure 213 to Figure 218 show the power factor as a function of supply voltage for each of the samples tested for the CFL types listed in Table 7. The CFLs tested, have a capacitive power factor.

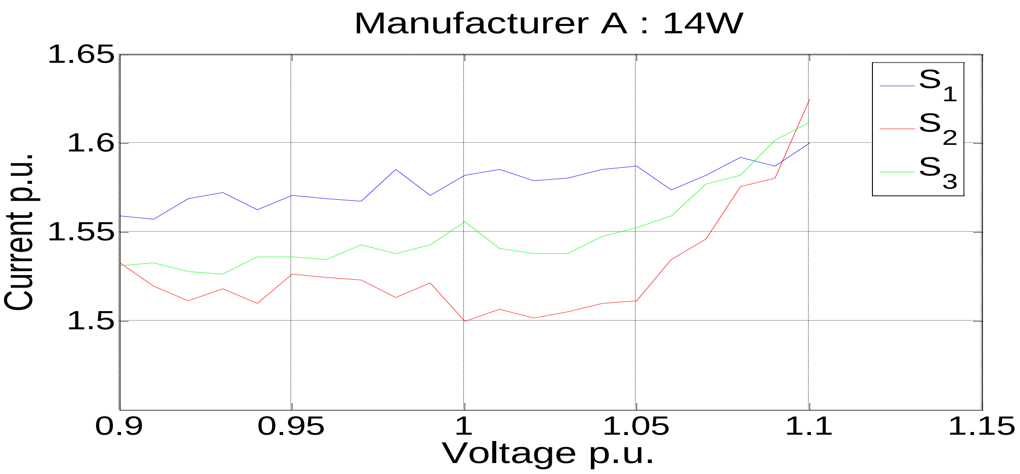

Figure 189: RMS supply current versus RMS supply voltage for the three 14 W CFL samples from manufacturer A.

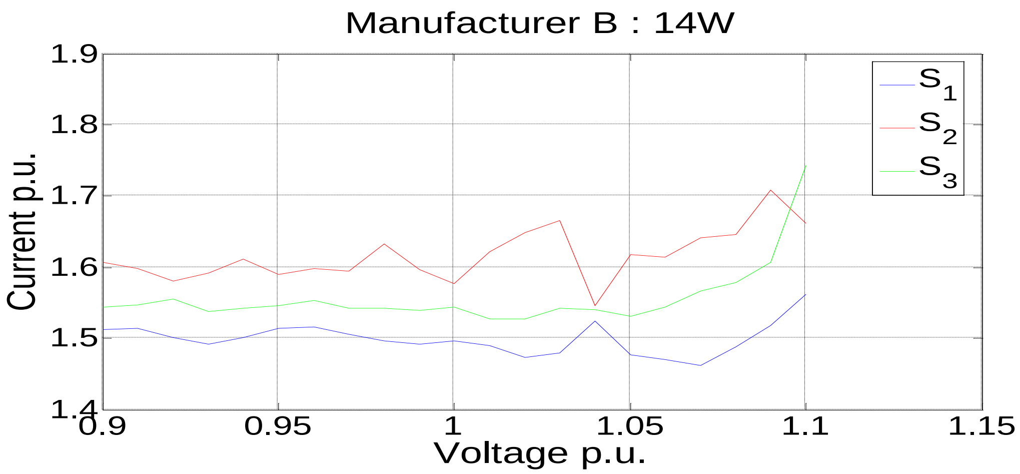

Figure 190: RMS supply current versus RMS supply voltage for the three 14 W CFL samples from manufacturer B.

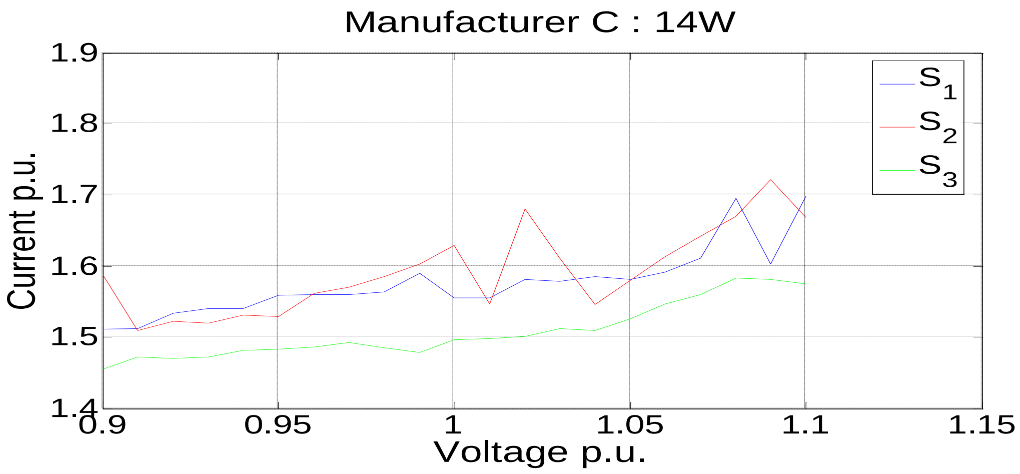

Figure 191: RMS supply current versus RMS supply voltage for the three 14 W CFL samples from manufacturer C.

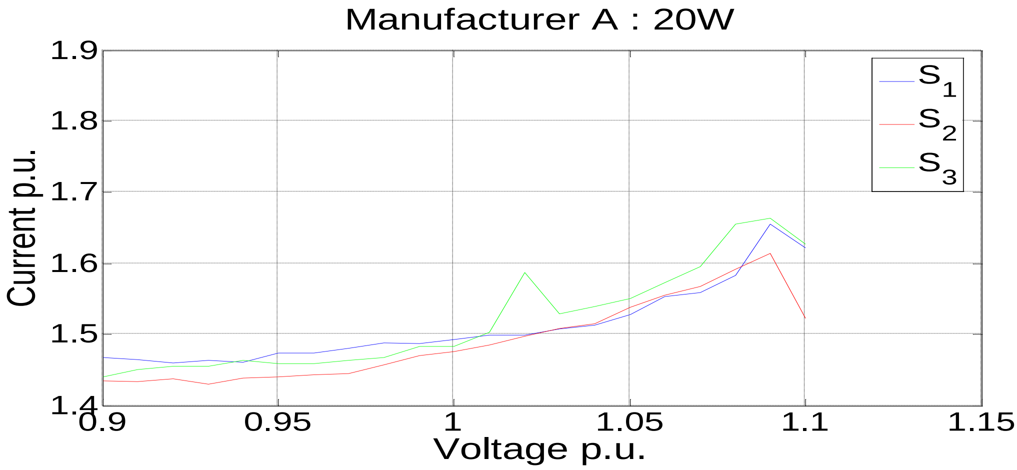

Figure 192: RMS supply current versus RMS supply voltage for the three 20 W CFL samples from manufacturer A.

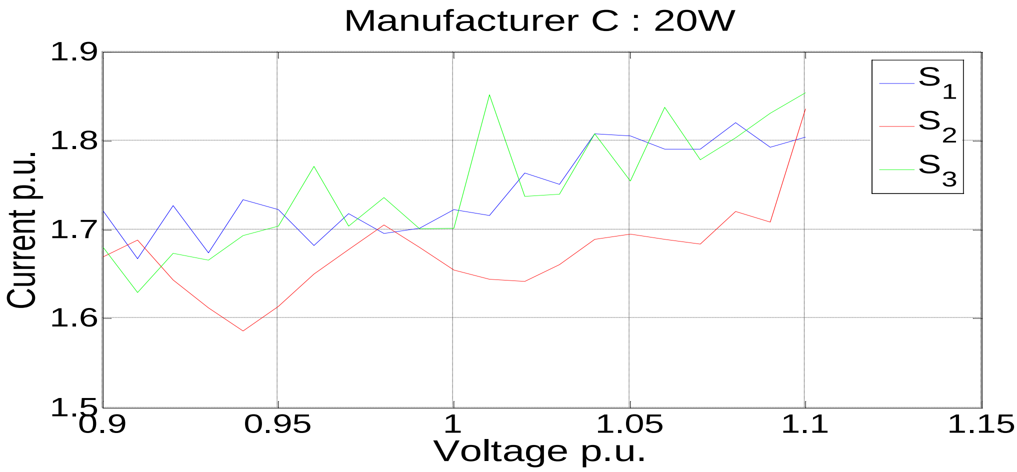

Figure 193: RMS supply current versus RMS supply voltage for the three 20 W CFL samples from manufacturer C.

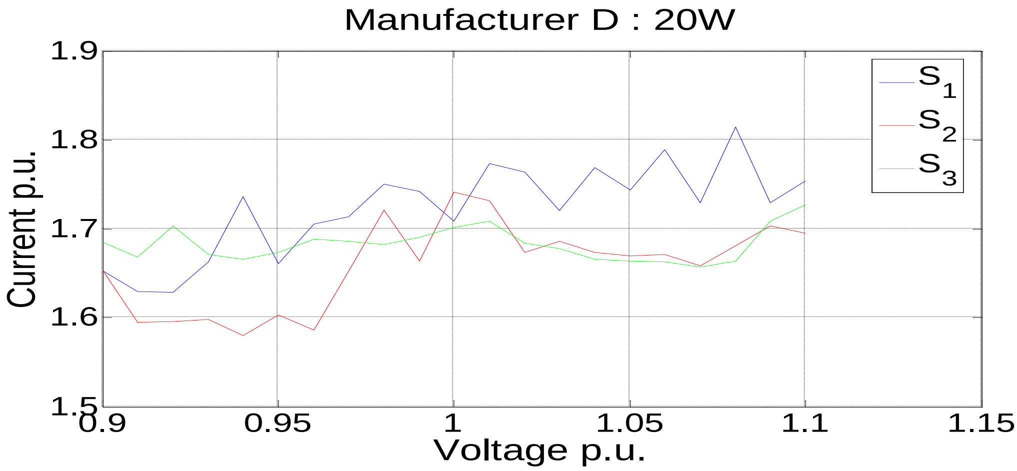

Figure 194: RMS supply current versus RMS supply voltage for the three 20 W CFL samples from manufacturer D.

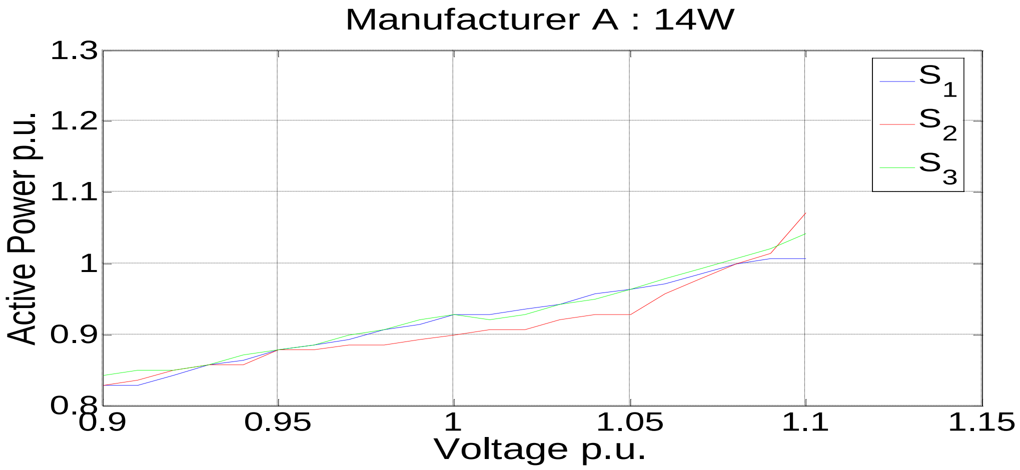

Figure 195: Active power versus RMS supply voltage for the three 14 W CFL samples from manufacturer A.

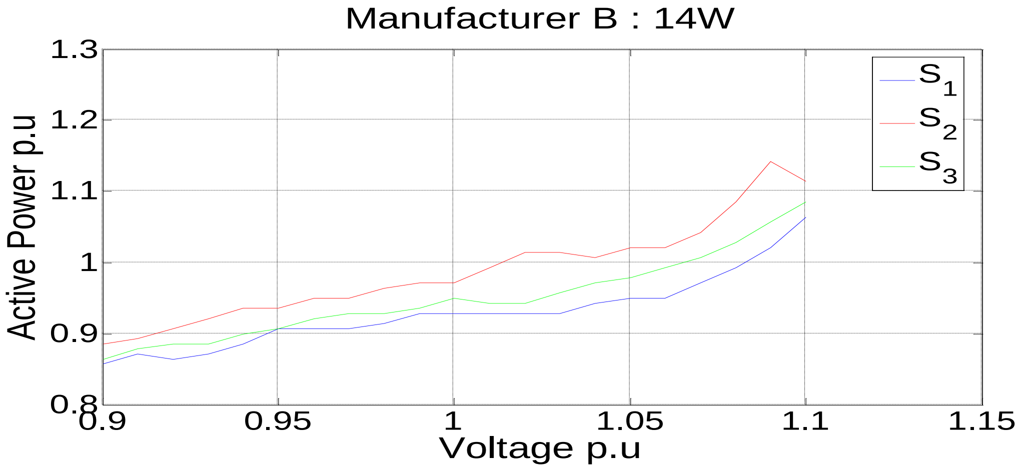

Figure 196: Active power versus RMS supply voltage for the three 14 W CFL samples from manufacturer B.

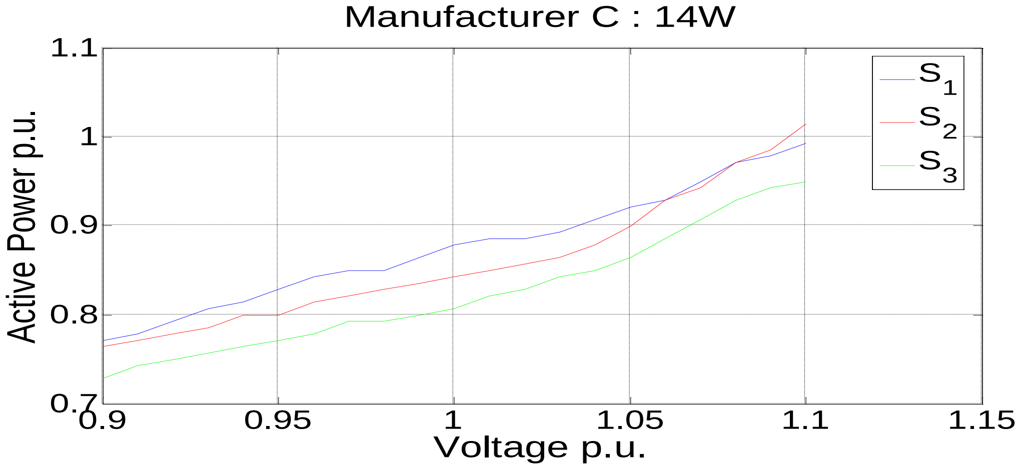

Figure 197: Active power versus RMS supply voltage for the three 14 W CFL samples from manufacturer C.

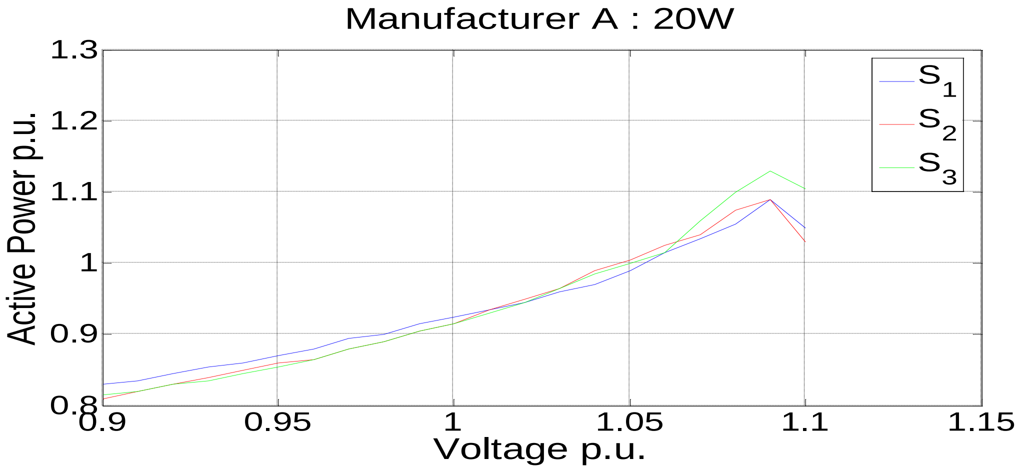

Figure 198: Active power versus RMS supply voltage for the three 20 W CFL samples from manufacturer A.

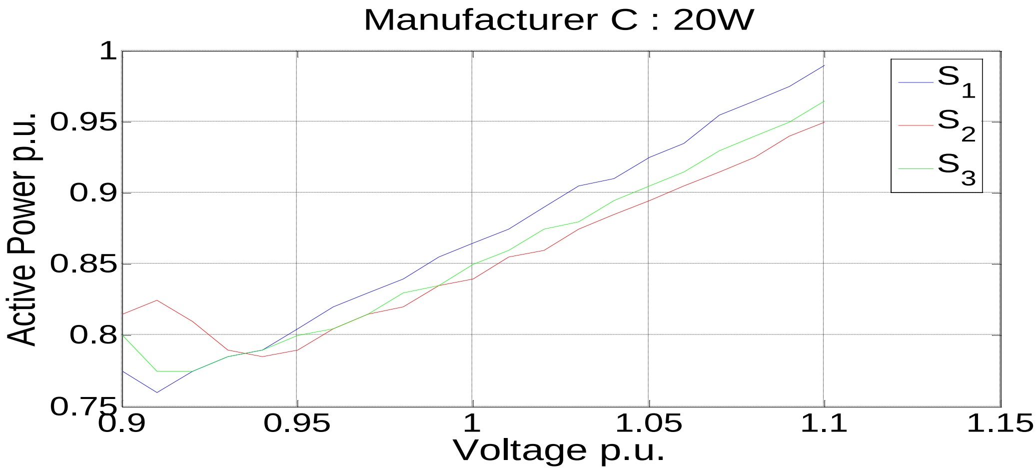

Figure 199: Active power versus RMS supply voltage for the three 20 W CFL samples from manufacturer C.

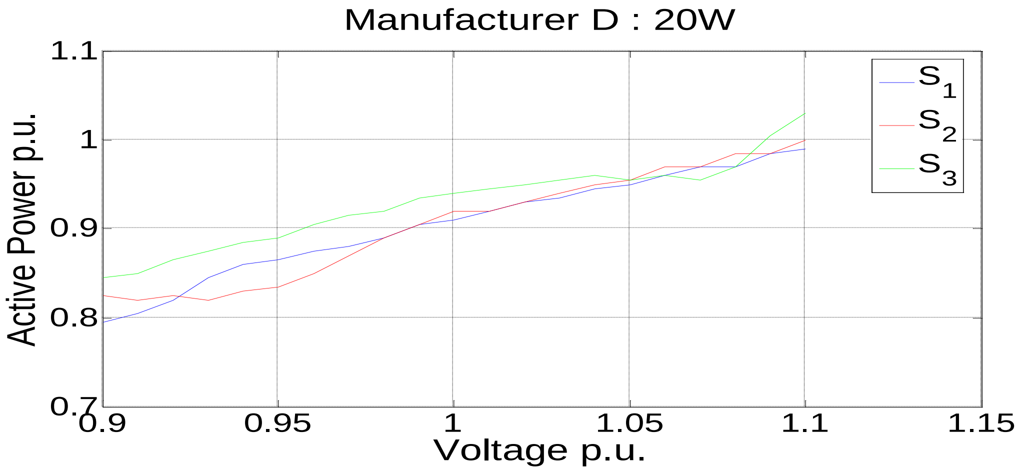

Figure 200: Active power versus RMS supply voltage for the three 20 W CFL samples from manufacturer D.

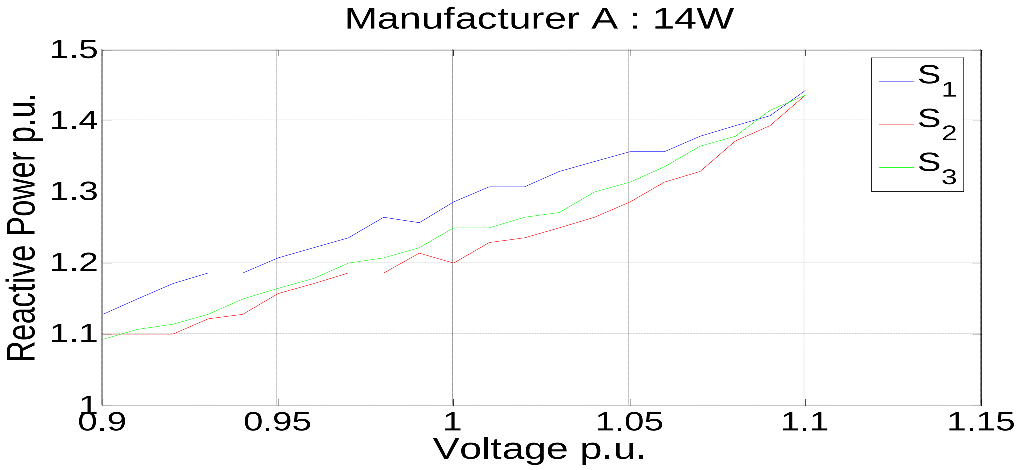

Figure 201: Reactive power versus RMS supply voltage for the three 14 W CFL samples from manufacturer A.

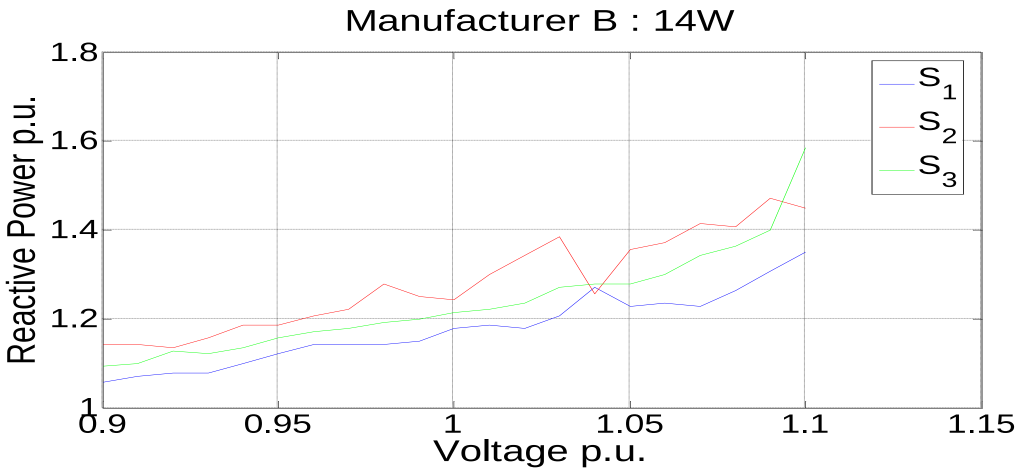

Figure 202: Reactive power versus RMS supply voltage for the three 14 W CFL samples from manufacturer B.

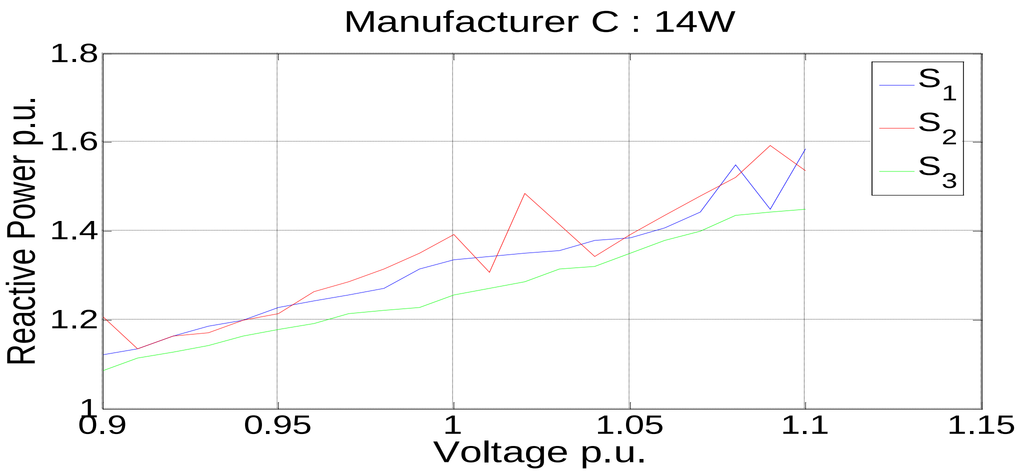

Figure 203: Reactive power versus RMS supply voltage for the three 14 W CFL samples from manufacturer C.

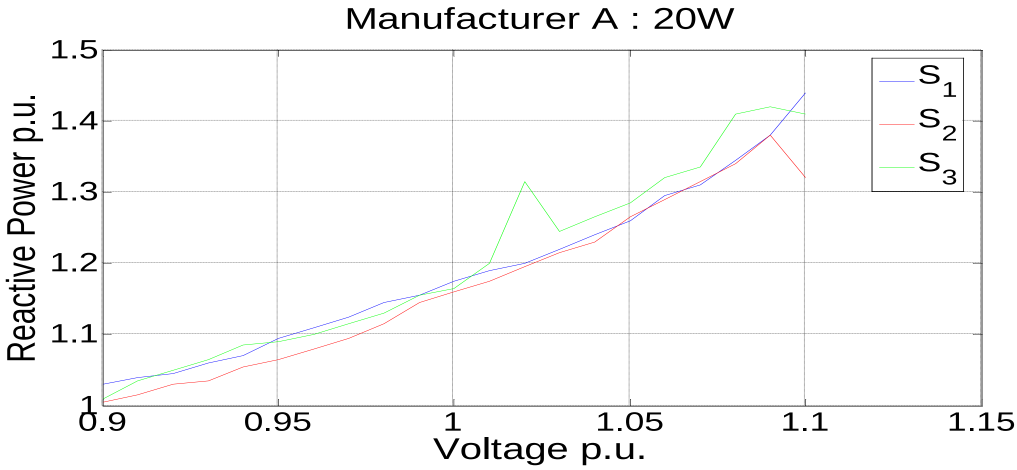

Figure 204: Reactive power versus RMS supply voltage for the three 20 W CFL samples from manufacturer A.

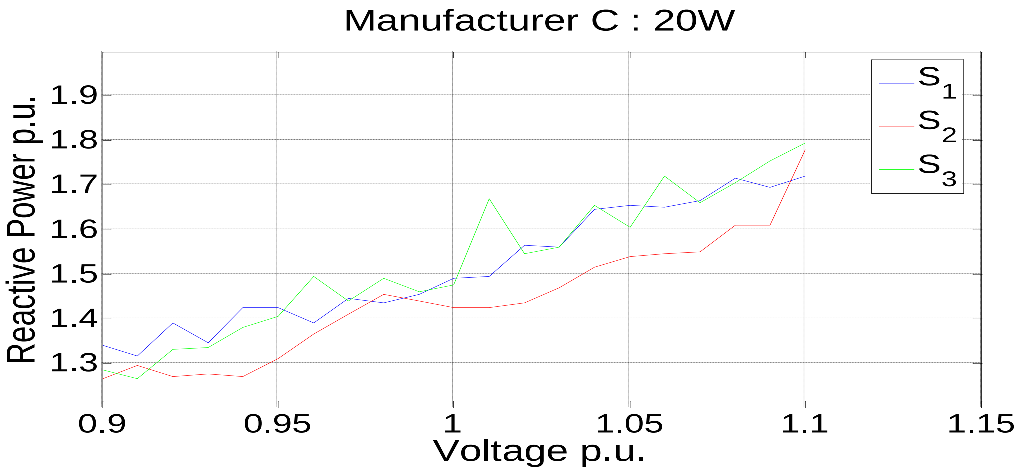

Figure 205: Reactive power versus RMS supply voltage for the three 20 W CFL samples from manufacturer C.

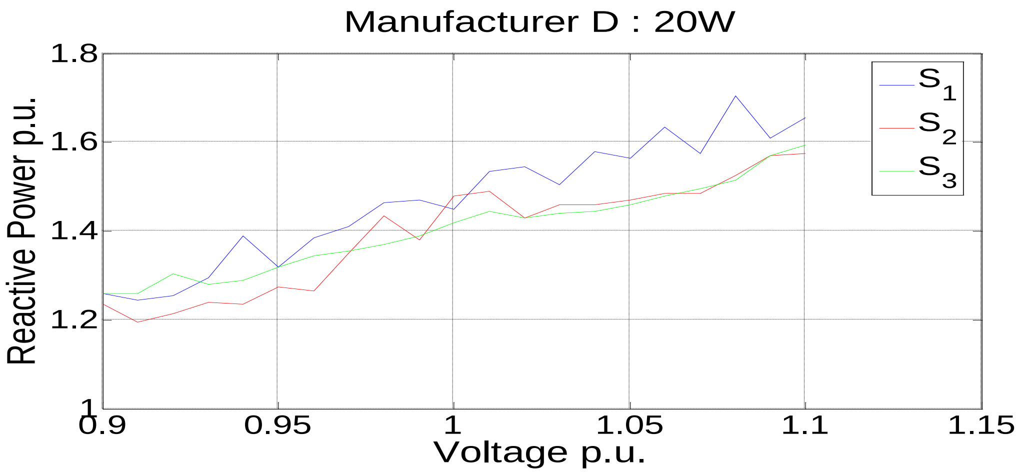

Figure 206: Reactive power versus RMS supply voltage for the three 20 W CFL samples from manufacturer D.

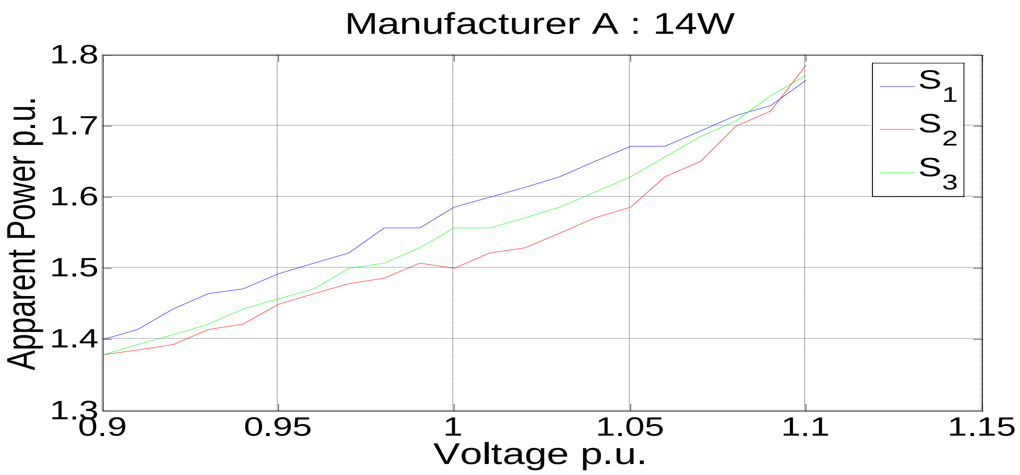

Figure 207: Apparent power versus RMS supply voltage for the three 14 W CFL samples from manufacturer A.

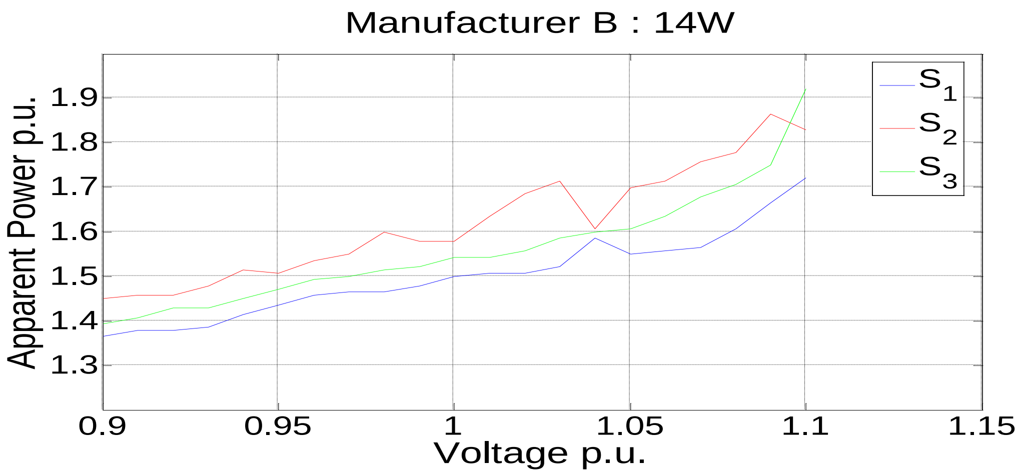

Figure 208: Apparent power versus RMS supply voltage for the three 14 W CFL samples from manufacturer B.

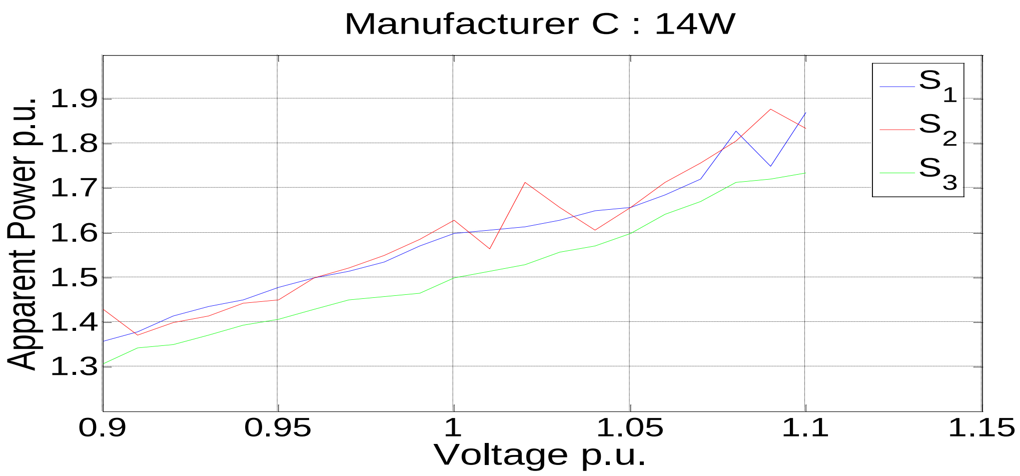

Figure 209: Apparent power versus RMS supply voltage for the three 14 W CFL samples from manufacturer C.

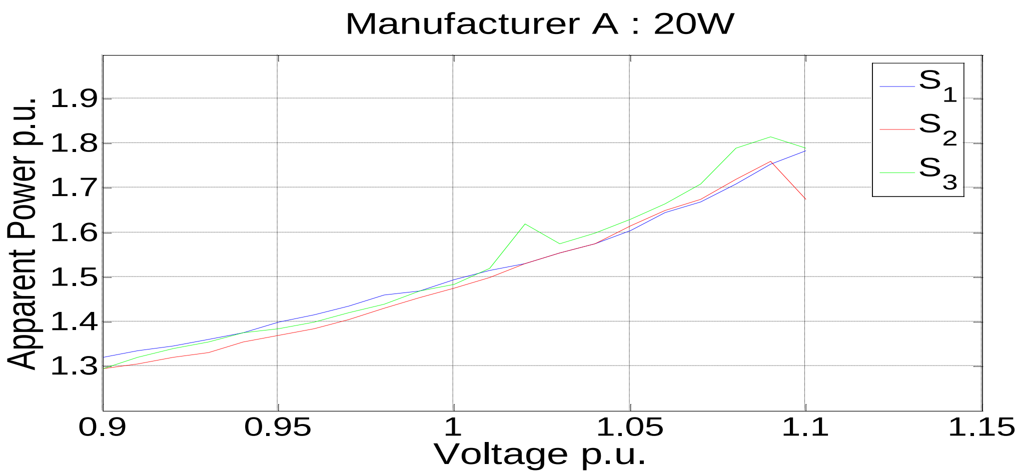

Figure 210: Apparent power versus RMS supply voltage for the three 20 W CFL samples from manufacturer A.

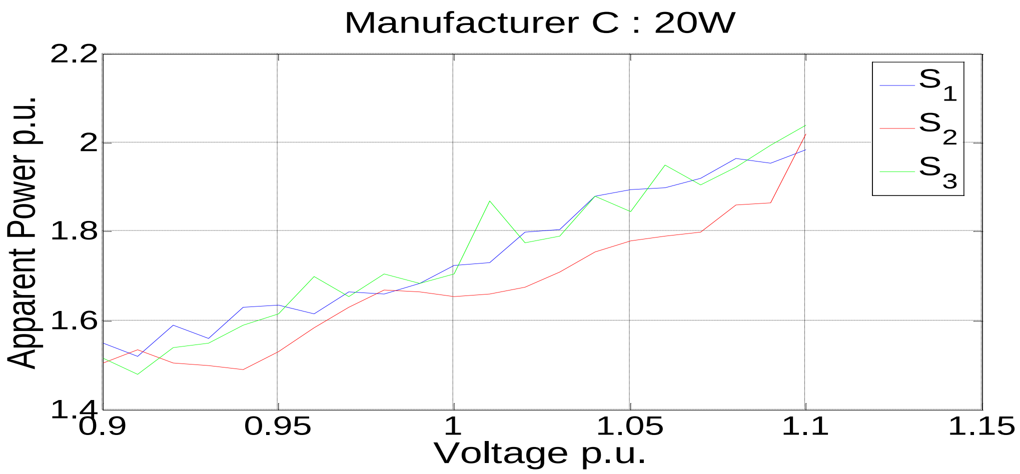

Figure 211: Apparent power versus RMS supply voltage for the three 20 W CFL samples from manufacturer C.

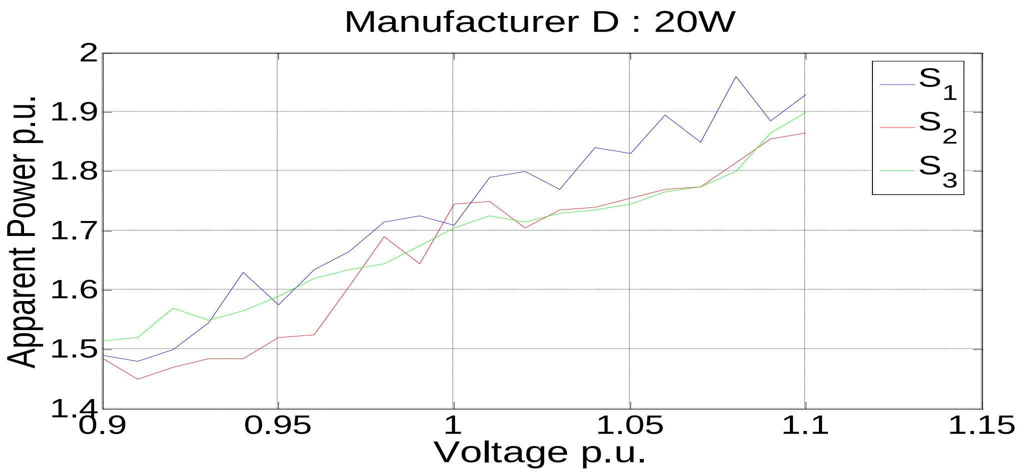

Figure 212: Apparent power versus RMS supply voltage for the three 20 W CFL samples from manufacturer D.

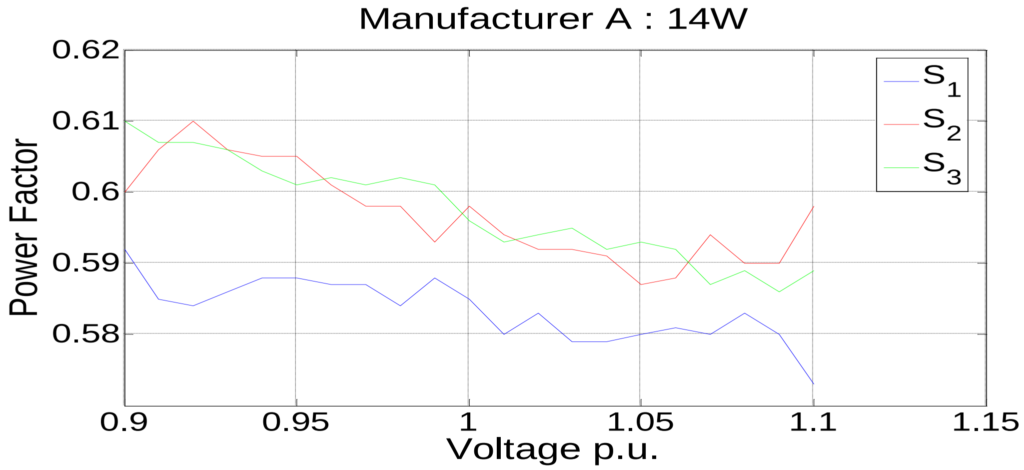

Figure 213: Power factor versus RMS supply voltage for the three 14 W CFL samples from manufacturer A.

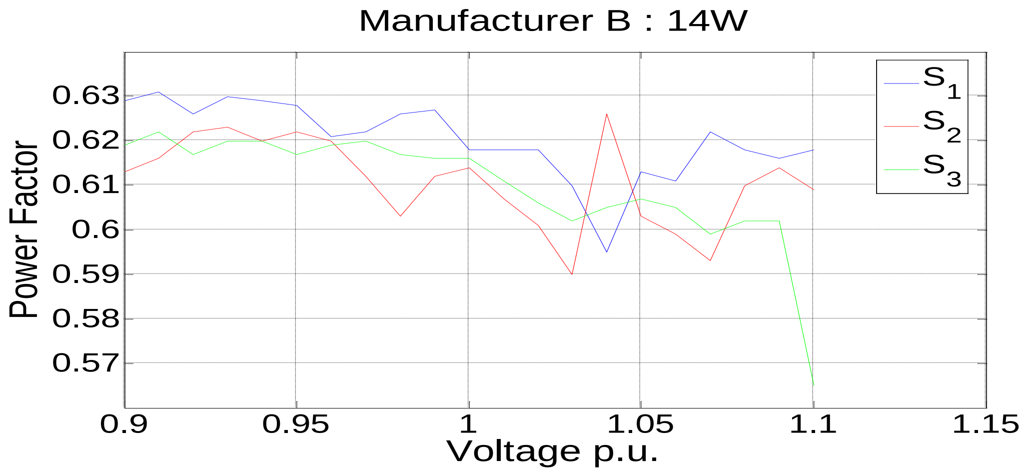

Figure 214: Power factor versus RMS supply voltage for the three 14 W CFL samples from manufacturer B.

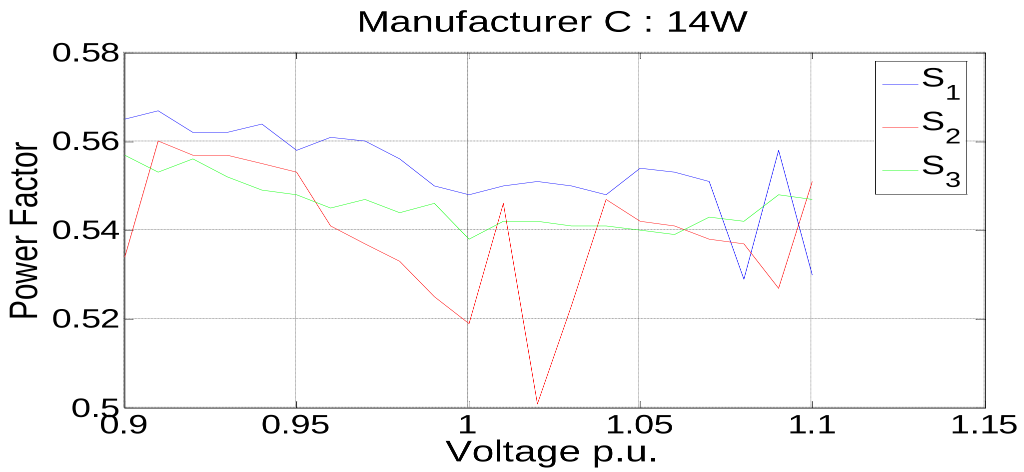

Figure 215: Power factor versus RMS supply voltage for the three 14 W CFL samples from manufacturer C.

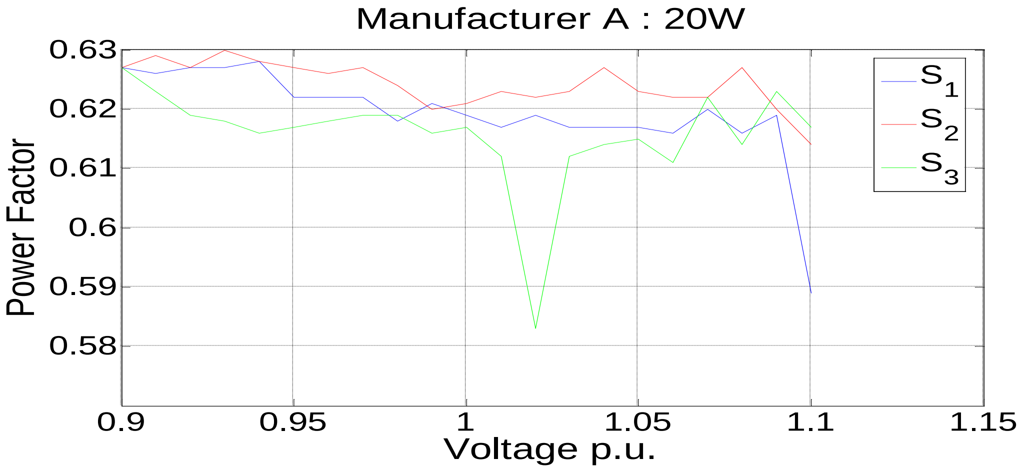

Figure 216: Power factor versus RMS supply voltage for the three 20 W CFL samples from manufacturer A.

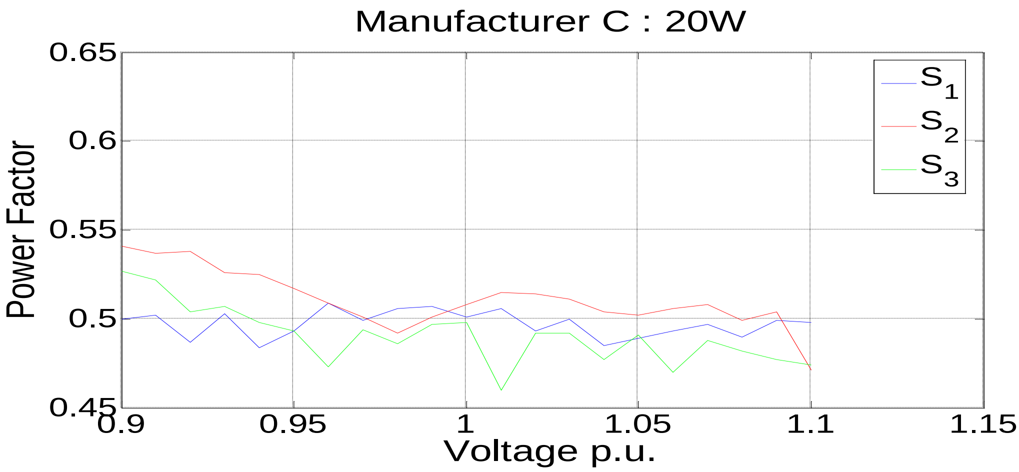

Figure 217: Power factor versus RMS supply voltage for the three 20 W CFL samples from manufacturer C.

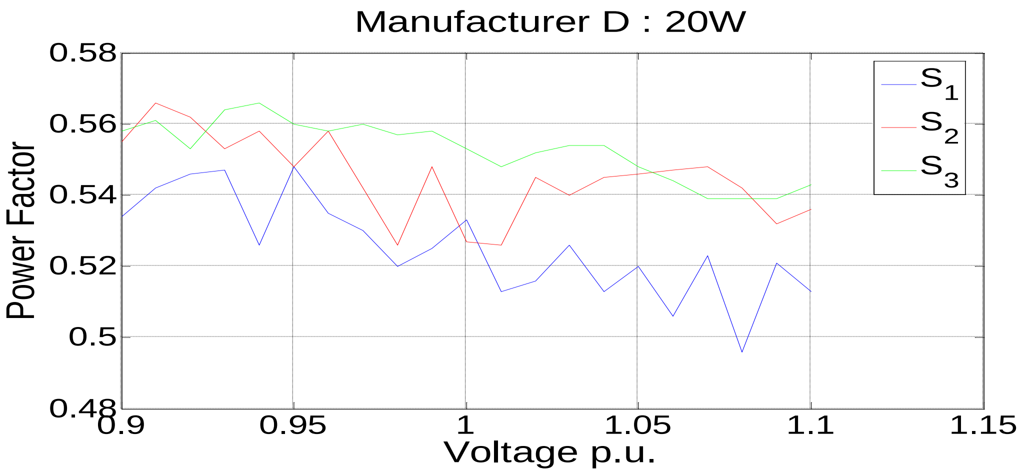

Figure 218: Power factor versus RMS supply voltage for the three 20 W CFL samples from manufacturer D.

A.3 Measurement results for Tubular Fluorescent Lamps with magnetic ballasts

Figure 219 to Figure 222 show the supply current as a function of the supply voltage for each of the samples (S_1, S_2, S_3) tested for the TFL types listed in Table 11. The base value for the current is determined by equation B.1-1.

Figure 223 to Figure 226 show the active power consumption as a function of supply voltage for each of the samples tested for the TFL types listed in Table 11. The base value for the active power is the rated power of the TFL.

Figure 227 to Figure 230 show the reactive power consumption as a function of supply voltage for each of the samples tested for the TFL types listed in Table 11. The base value for the reactive power is the rated power of the TFL.

Figure 231 to Figure 234 show the apparent power consumption as a function of supply voltage for each of the samples tested for the TFL types listed in Table 11. The base value for the apparent power is the rated power of the TFL.

Figure 235 to Figure 238 show the power factor as a function of supply voltage for each of the samples tested for the TFL types listed in Table 11. As a result of the power factor correction capacitor, the TFLs tested have a capacitive power factor.

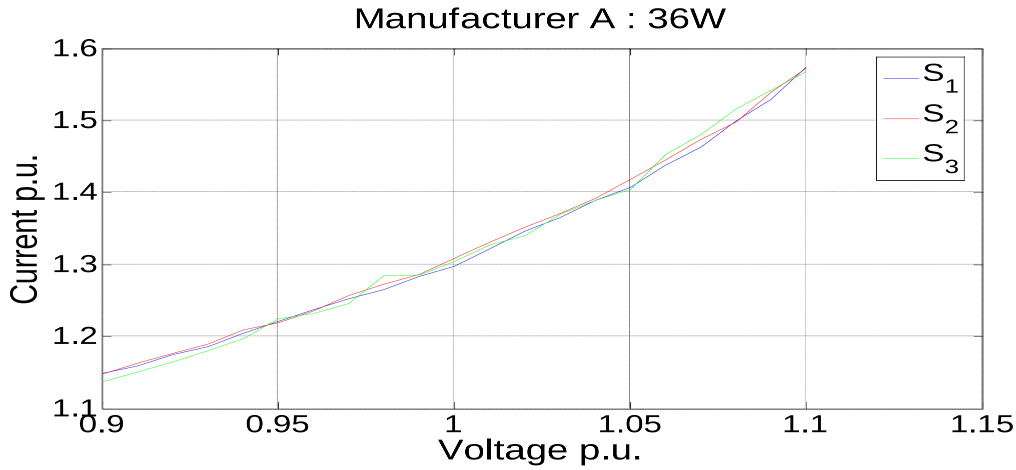

Figure 219: RMS supply current versus RMS supply voltage for the three 36 W TFL samples from manufacturer A and magnetic ballast alpha.

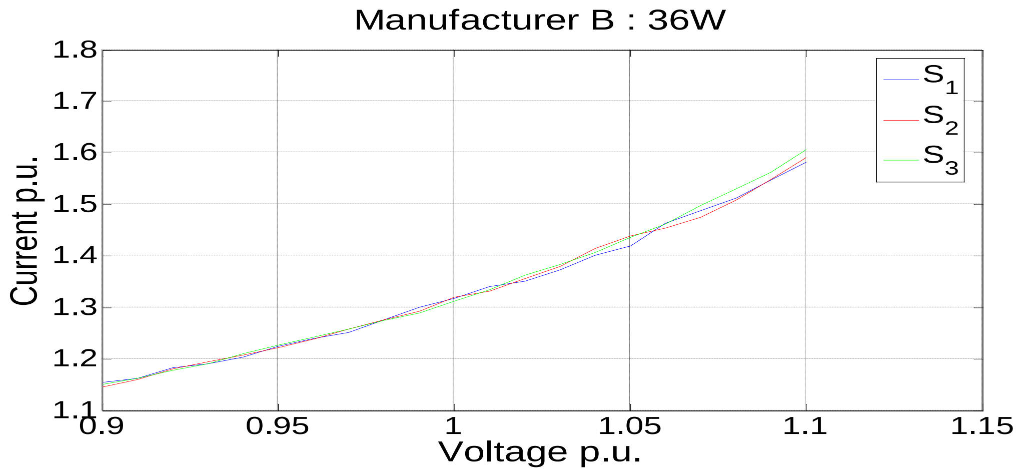

Figure 220: RMS supply current versus RMS supply voltage for the three 36 W TFL samples from manufacturer B and magnetic ballast alpha.

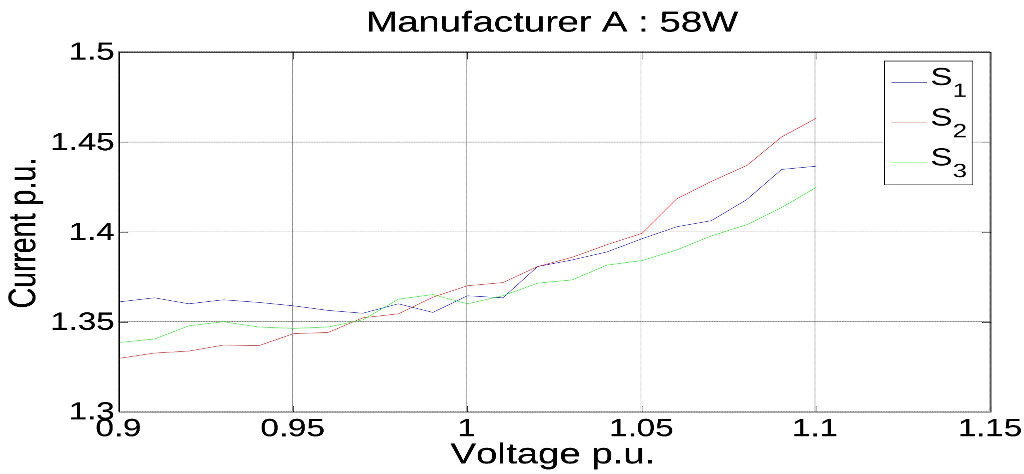

Figure 221: RMS supply current versus RMS supply voltage for the three 58 W TFL samples from manufacturer A and magnetic ballast alpha.

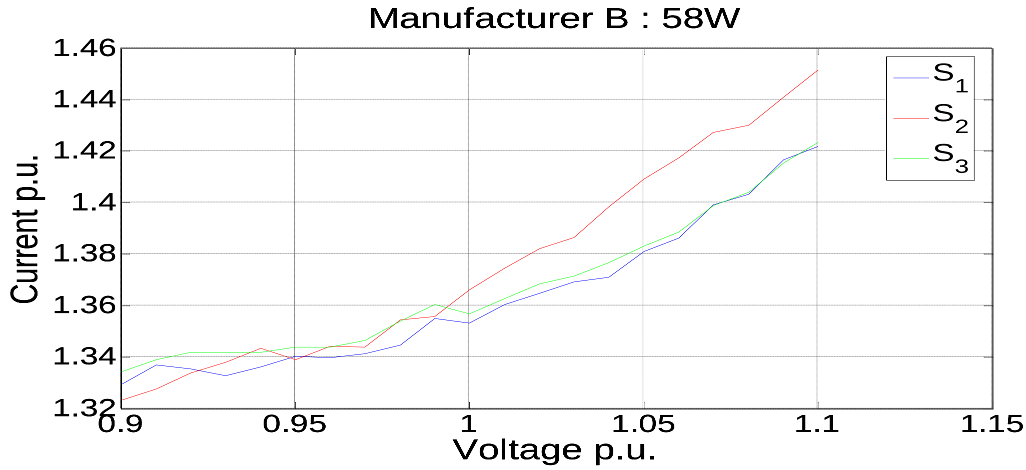

Figure 222: RMS supply current versus RMS supply voltage for the three 58 W TFL samples from manufacturer B and magnetic ballast alpha.

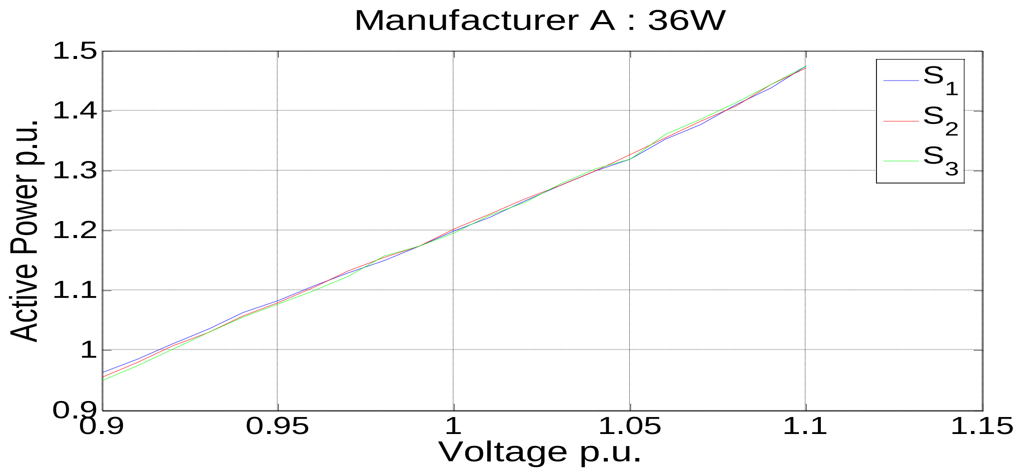

Figure 223: Active power versus RMS supply voltage for the three 36 W TFL samples from manufacturer A and magnetic ballast alpha.

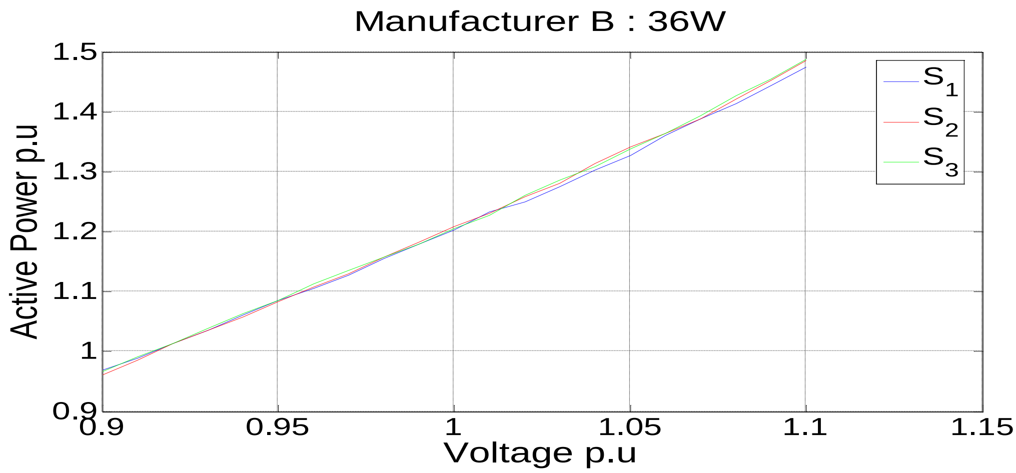

Figure 224: Active power versus RMS supply voltage for the three 36 W TFL samples from manufacturer B and magnetic ballast alpha.

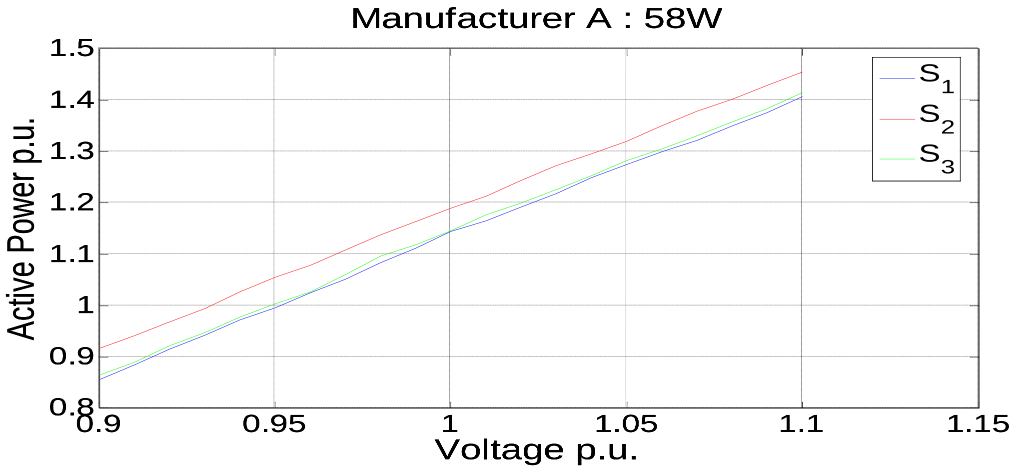

Figure 225: Active power versus RMS supply voltage for the three 58 W TFL samples from manufacturer A and magnetic ballast alpha.

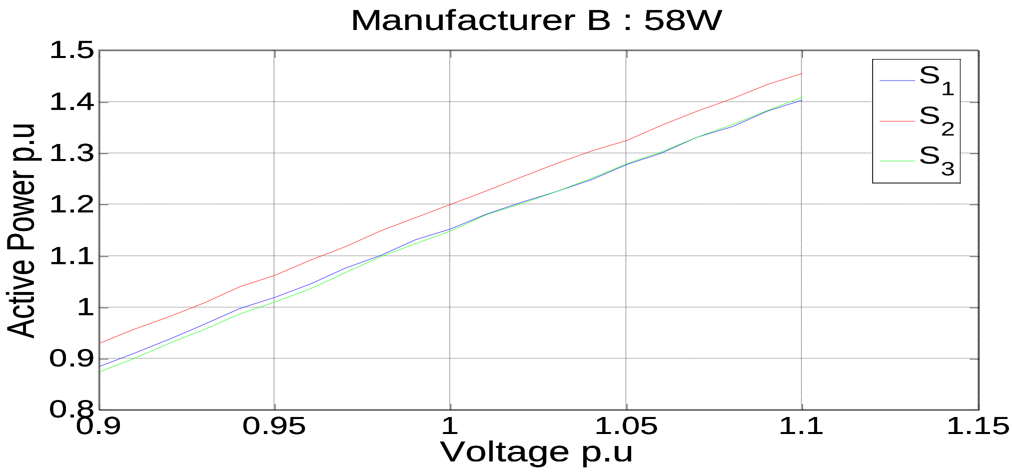

Figure 226: Active power versus RMS supply voltage for the three 58 W TFL samples from manufacturer B and magnetic ballast alpha.

Figure 227: Reactive power versus RMS supply voltage for the three 36 W TFL samples from manufacturer A and magnetic ballast alpha.

Figure 228: Reactive power versus RMS supply voltage for the three 36 W TFL samples from manufacturer B and magnetic ballast alpha.

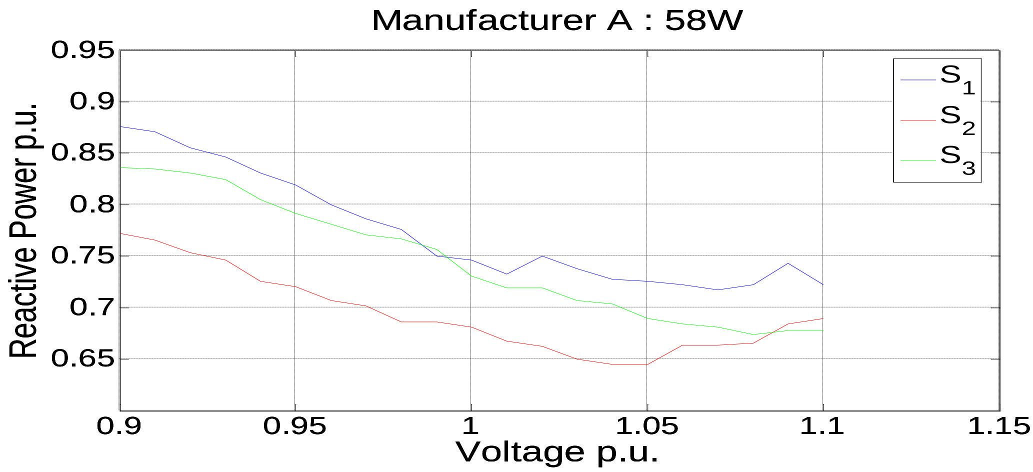

Figure 229: Reactive power versus RMS supply voltage for the 58 W TFL samples from manufacturer A and magnetic ballast alpha.

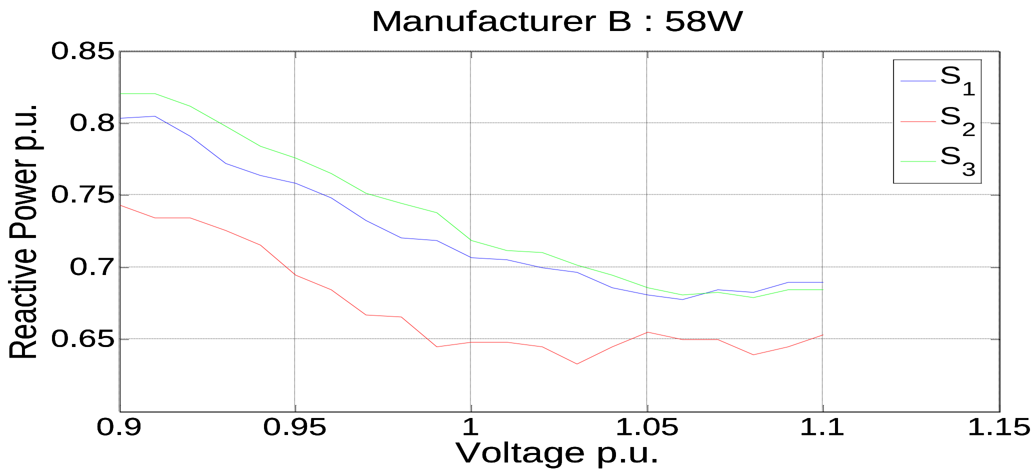

Figure 230: Reactive power versus RMS supply voltage for the three 58 W TFL samples from manufacturer B and magnetic ballast alpha.

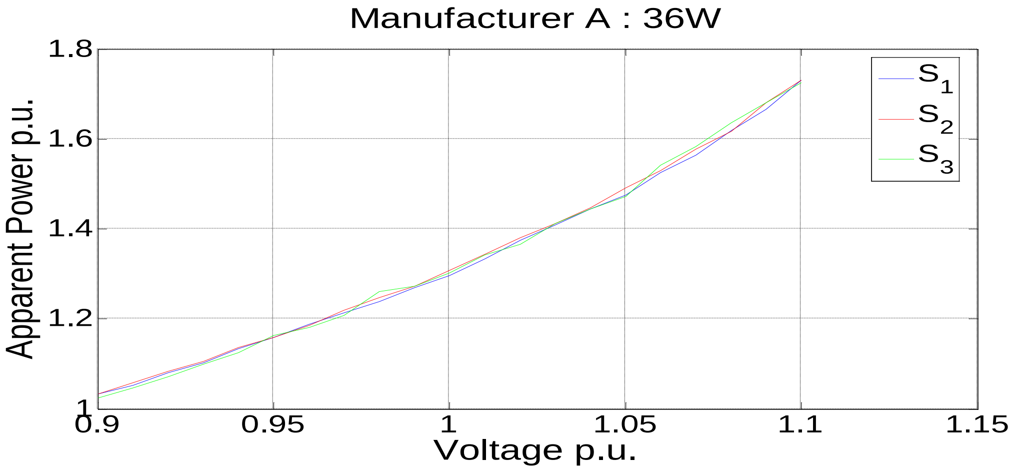

Figure 231: Apparent power versus RMS supply voltage for the three 36 W TFL samples from manufacturer A and magnetic ballast alpha.

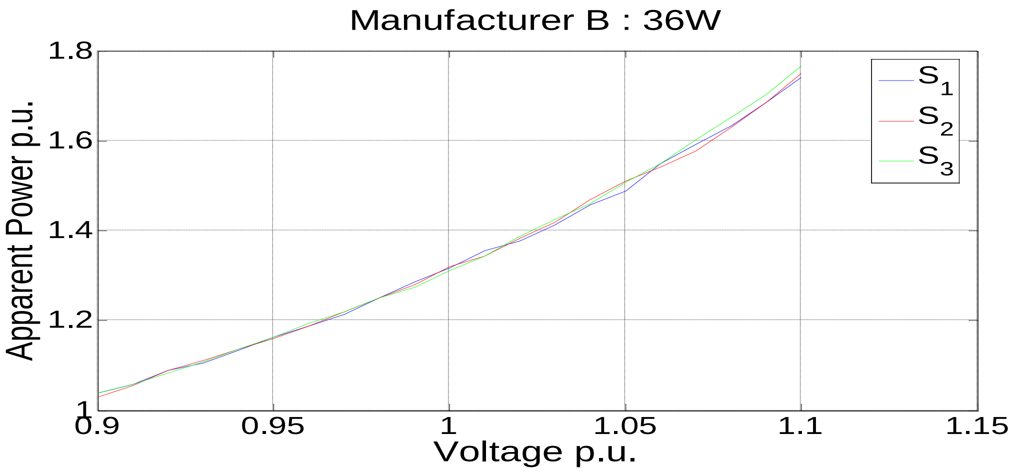

Figure 232: Apparent power versus RMS supply voltage for the three 36 W TFL samples from manufacturer B and magnetic ballast alpha.

Figure 233: Apparent power versus RMS supply voltage for the three 58 W TFL samples from manufacturer A and magnetic ballast alpha.

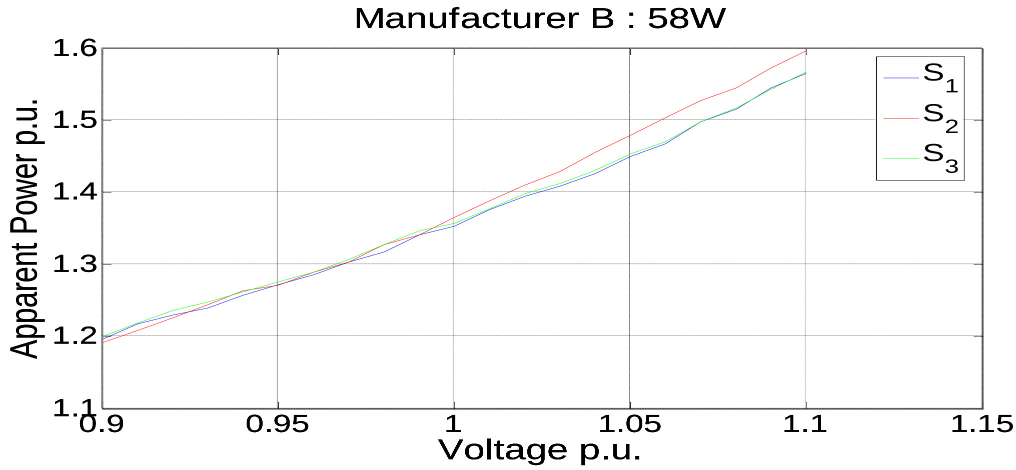

Figure 234: Apparent power versus RMS supply voltage for the three 58 W TFL samples from manufacturer B and magnetic ballast alpha.

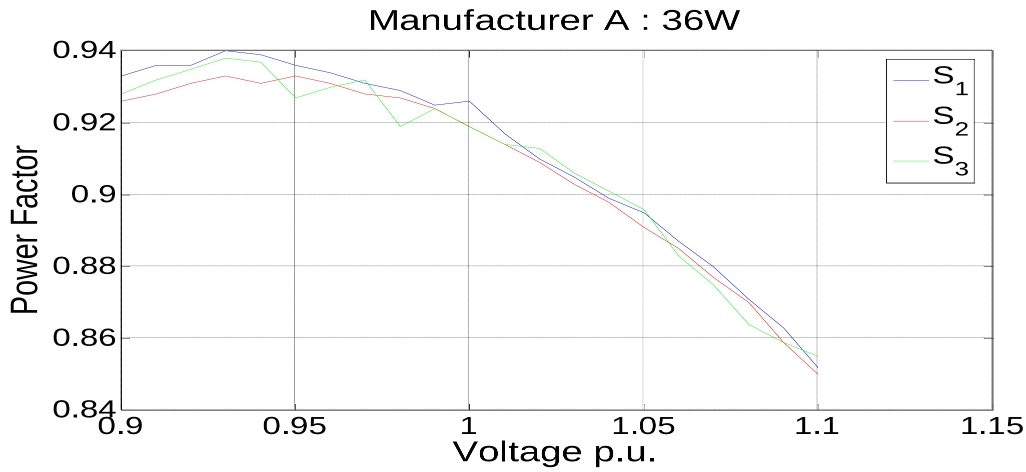

Figure 235: Power factor versus RMS supply voltage for the three 36 W TFL samples from manufacturer A and magnetic ballast alpha.

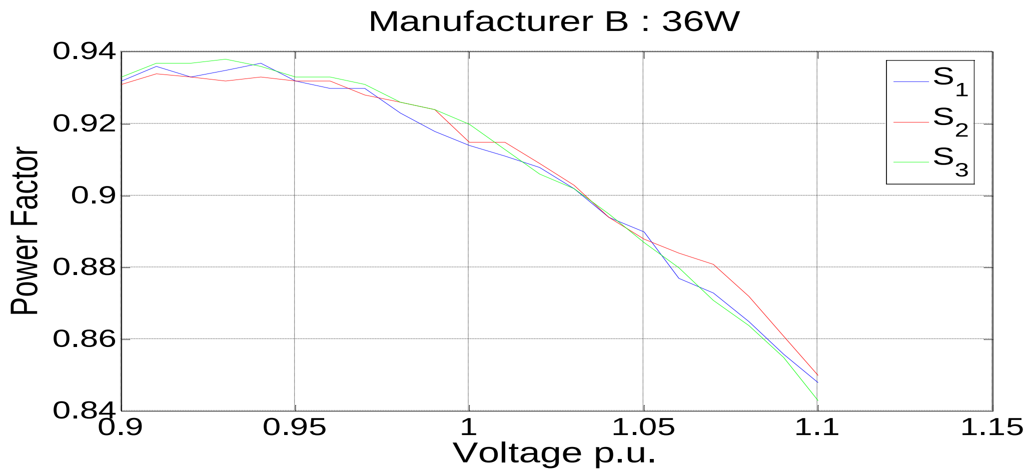

Figure 236: Power factor versus RMS supply voltage for the three 36 W TFL samples from manufacturer B and magnetic ballast alpha.

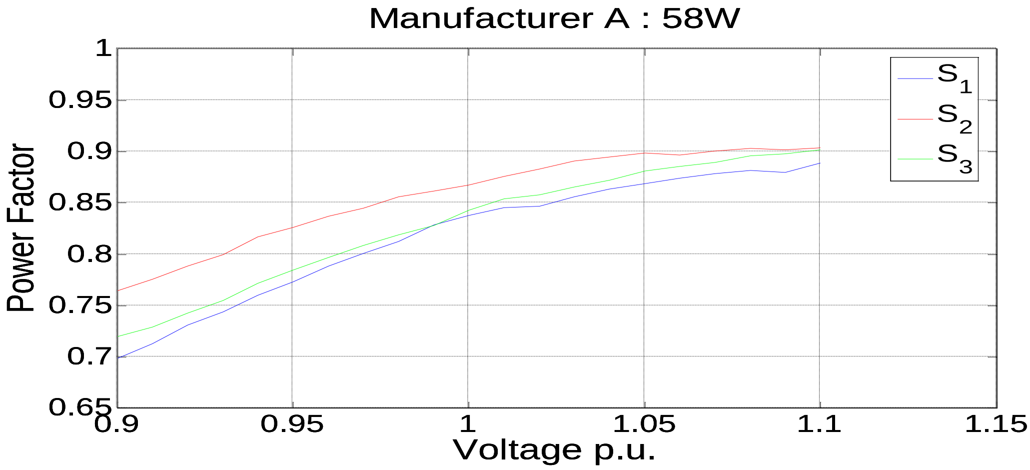

Figure 237: Power factor versus RMS supply voltage for the three 58 W TFL samples from manufacturer A and magnetic ballast alpha.

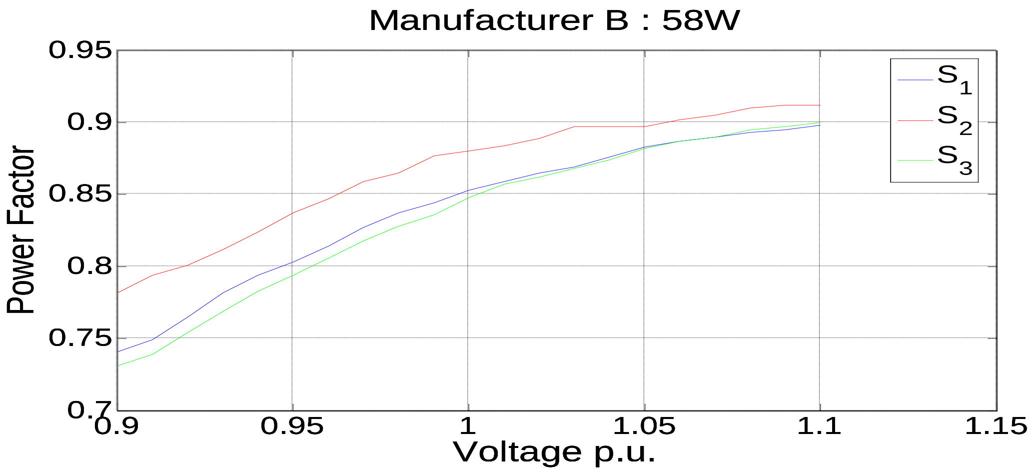

Figure 238: Power factor versus RMS supply voltage for the three 58 W TFL samples from manufacturer B and magnetic ballast alpha.

A.4 Measurement results for Tubular Fluorescent Lamps with electronic ballasts

Figure 239 to Figure 242 show the supply current as a function of the supply voltage for each of the samples (S_1, S_2, S_3) tested for the TFL types listed in Table 11. The base value for the current is determined by equation B.1-1.

Figure 243 to Figure 246 show the active power consumption as a function of supply voltage for each of the samples tested for the TFL types listed in Table 11. The base value for the active power is the rated power of the TFL.

Figure 247 to Figure 250 show the reactive power consumption as a function of supply voltage for each of the samples tested for the TFL types listed in Table 11. The base value for the reactive power is the rated power of the TFL.

Figure 251 to Figure 254 show the apparent power consumption as a function of supply voltage for each of the samples tested for the TFL types listed in Table 11. The base value for the apparent power is the rated power of the TFL.

Figure 255 to Figure 258 show the power factor as a function of supply voltage for each of the samples tested for the TFL types listed in Table 11. The TFLs tested have a capacitive power factor.

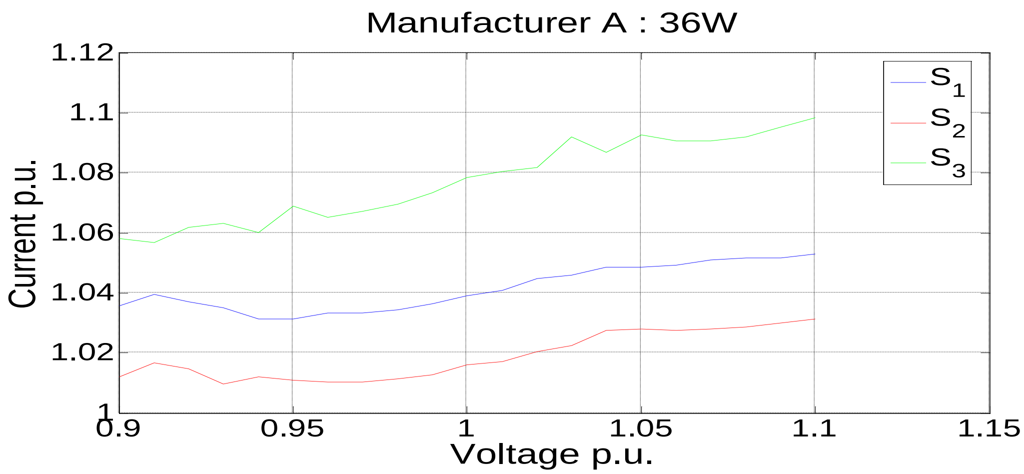

Figure 239: RMS supply current versus RMS supply voltage for the three 36 W TFL samples from manufacturer A and electronic ballast alpha.

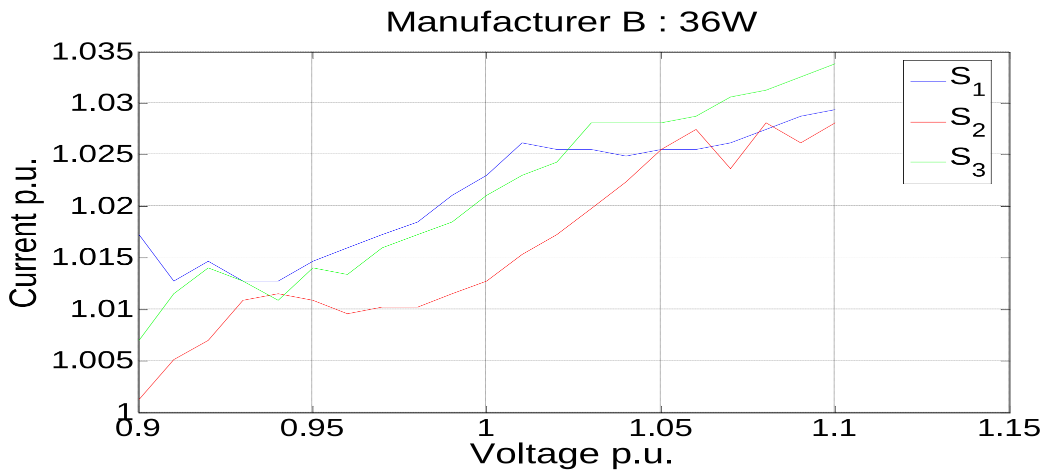

Figure 240: RMS supply current versus RMS supply voltage for the three 36 W TFL samples from manufacturer B and electronic ballast alpha.

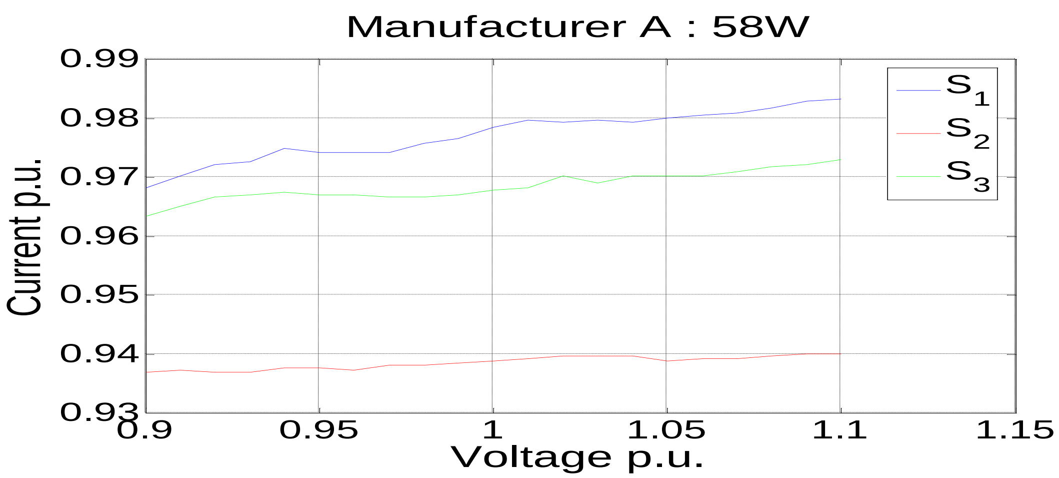

Figure 241: RMS supply current versus RMS supply voltage for the three 58 W TFL samples from manufacturer A and electronic ballast alpha.

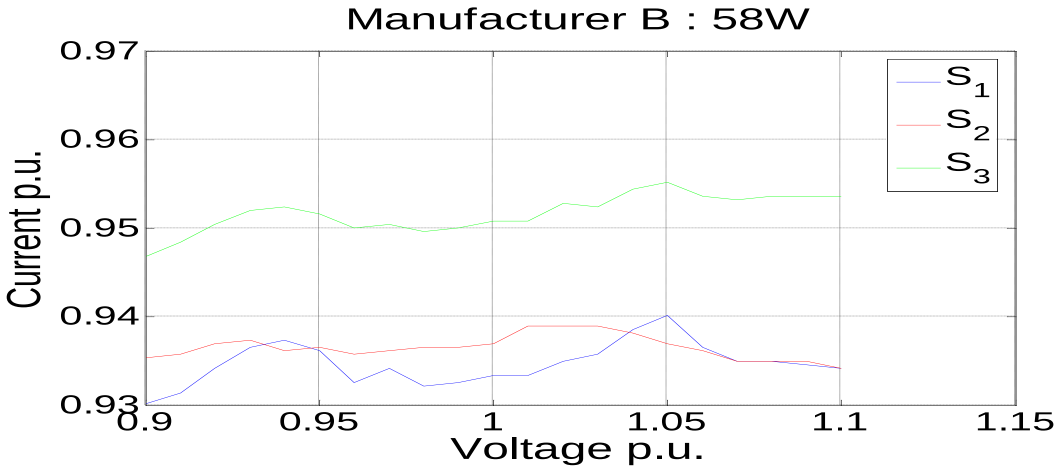

Figure 242: RMS supply current versus RMS supply voltage for the three 58 W TFL samples from manufacturer B and electronic ballast alpha.

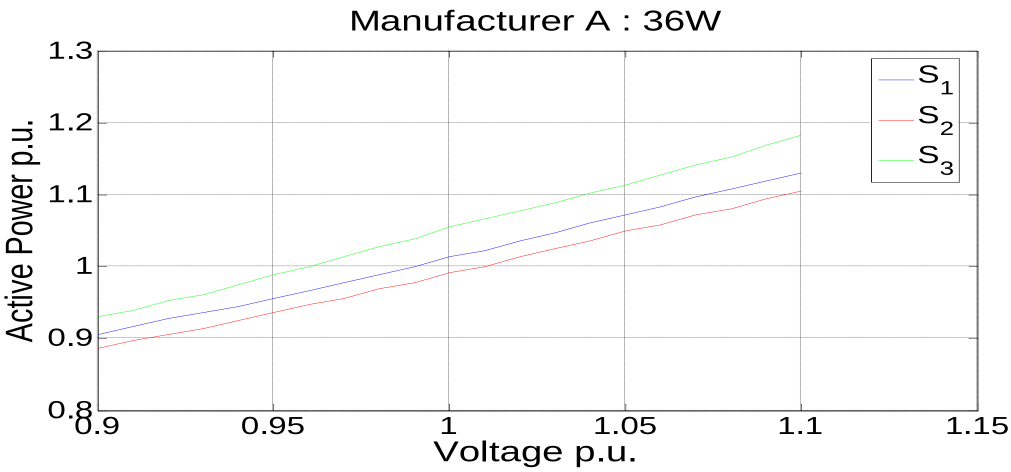

Figure 243: Active power versus RMS supply voltage for the three 36 W TFL samples from manufacturer A and electronic ballast alpha.

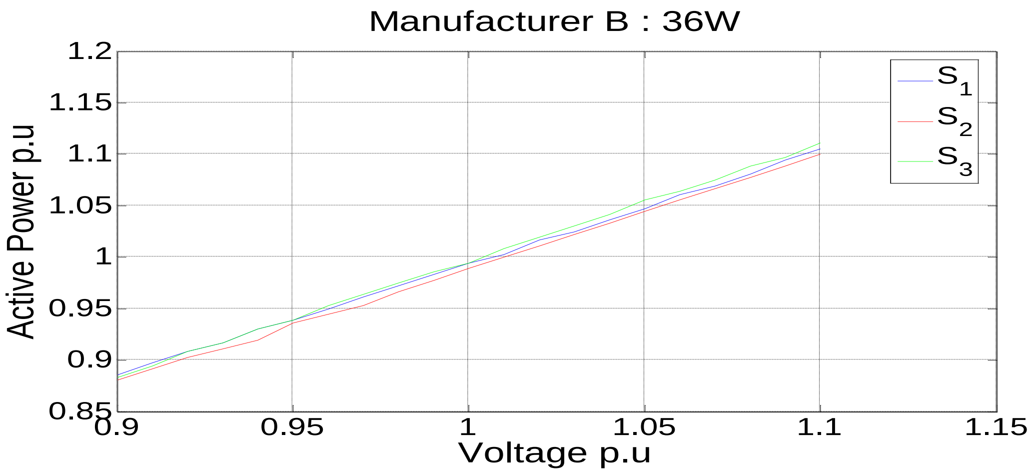

Figure 244: Active power versus RMS supply voltage for the three 36 W TFL samples from manufacturer B and electronic ballast alpha.

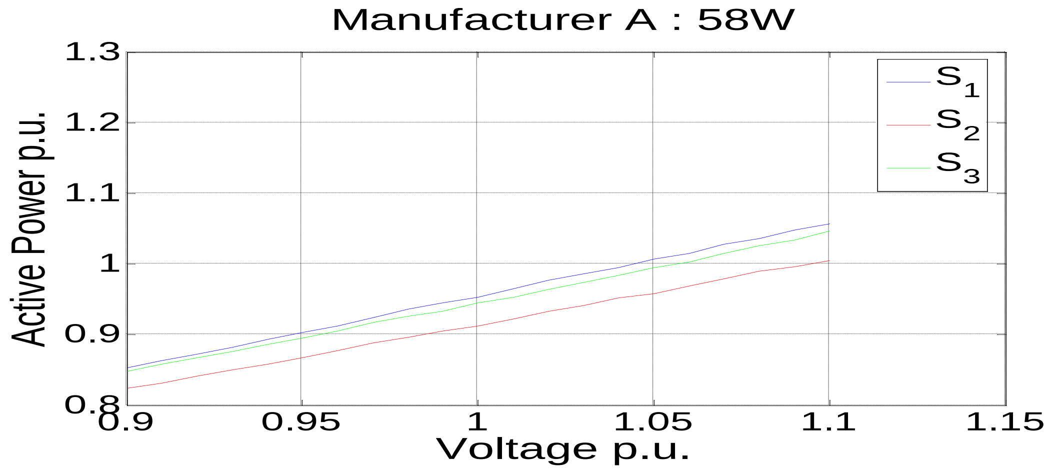

Figure 245: Active power versus RMS supply voltage for the three 58 W TFL samples from manufacturer A and electronic ballast alpha.

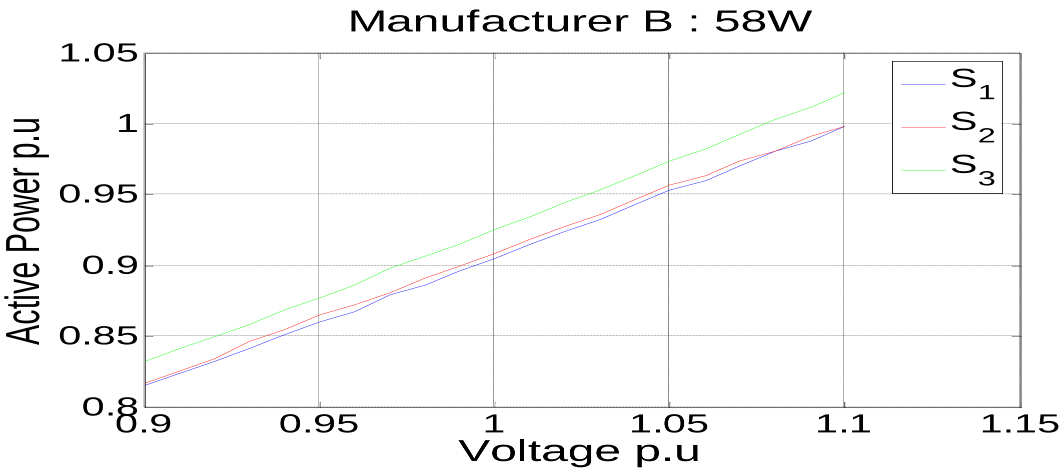

Figure 246: Active power versus RMS supply voltage for the three 58 W TFL samples from manufacturer B and electronic ballast alpha.

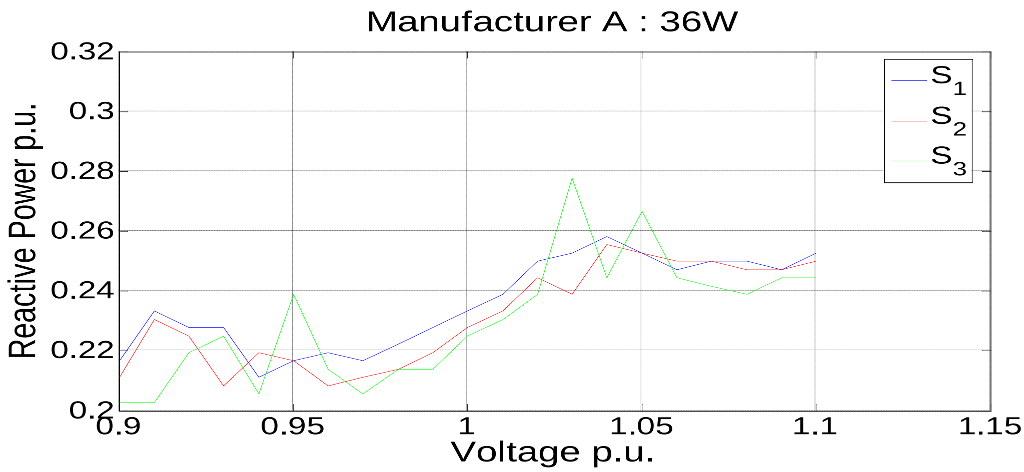

Figure 247: Reactive power versus RMS supply voltage for the three 36 W TFL samples from manufacturer A and electronic ballast alpha.

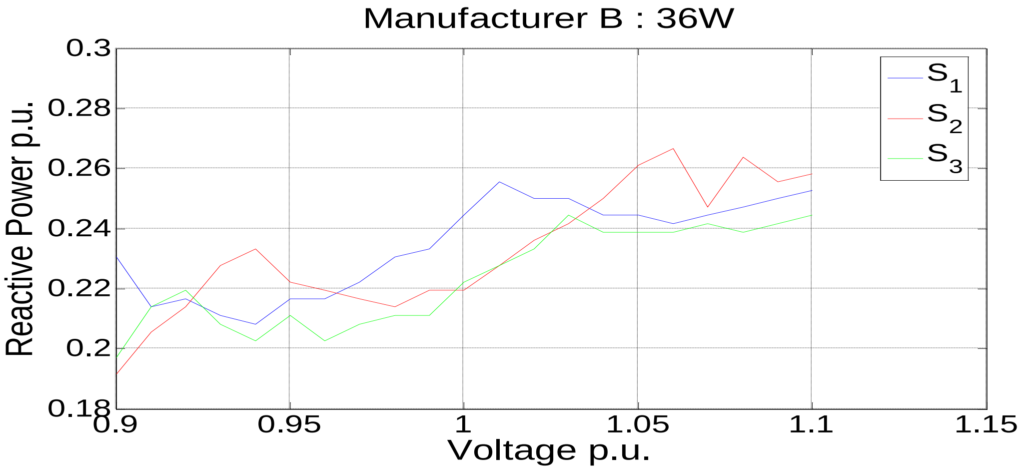

Figure 248: Reactive power versus RMS supply voltage for the three 36 W TFL samples from manufacturer B and electronic ballast alpha.

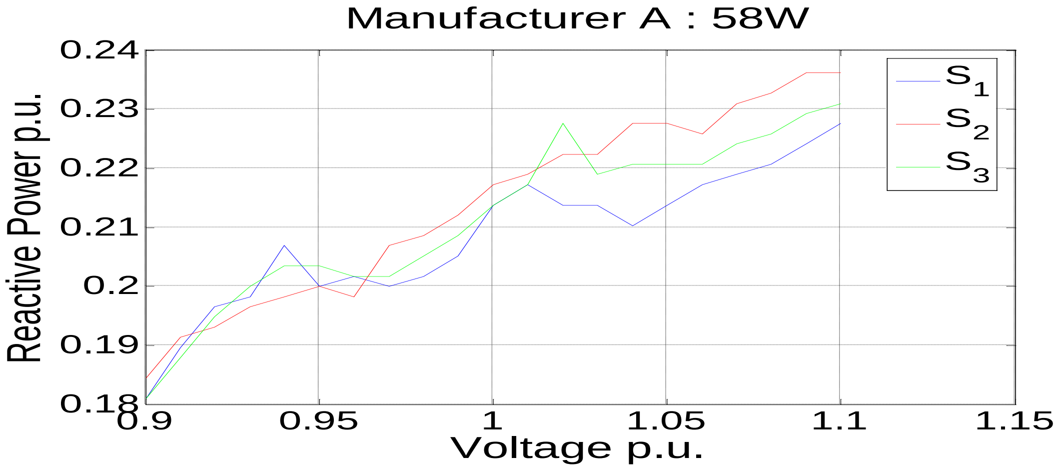

Figure 249: Reactive power versus RMS supply voltage for the 58 W TFL samples from manufacturer A and electronic ballast alpha.

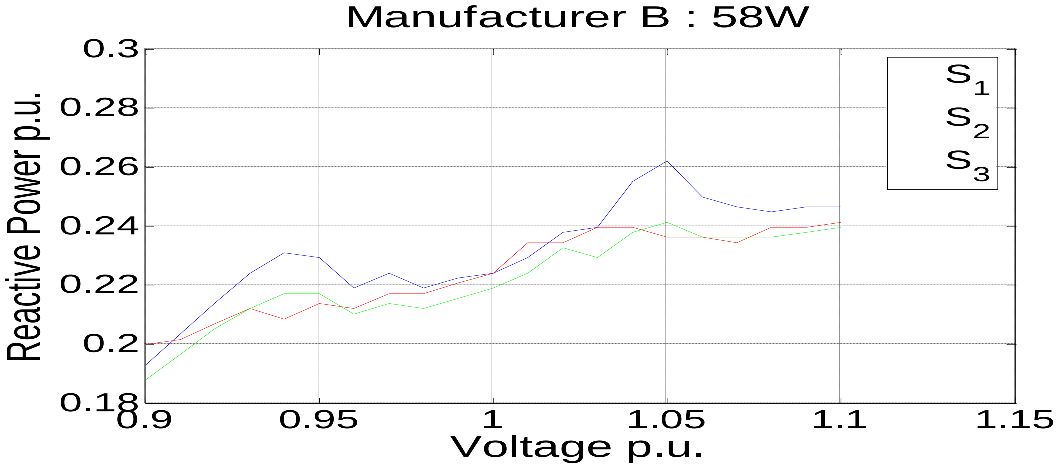

Figure 250: Reactive power versus RMS supply voltage for the three 58 W TFL samples from manufacturer B and electronic ballast alpha.

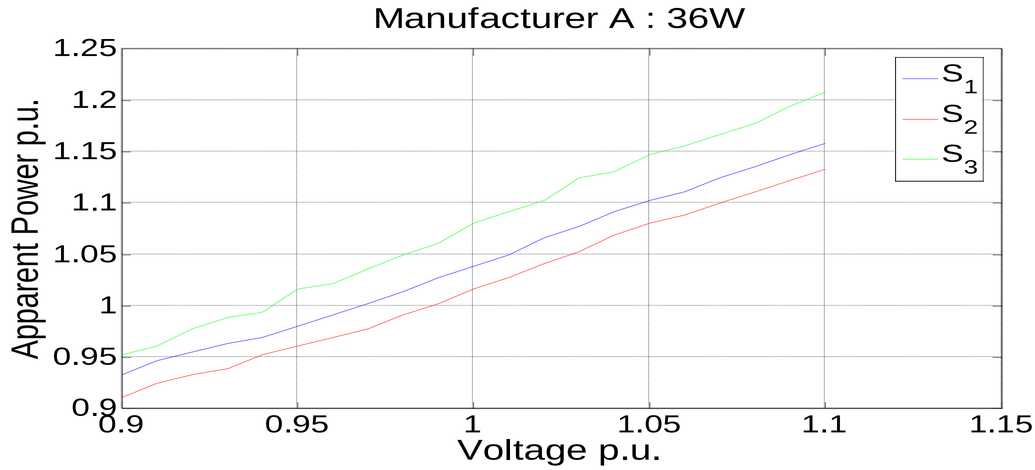

Figure 251: Apparent power versus RMS supply voltage for the three 36 W TFL samples from manufacturer A and electronic ballast alpha.

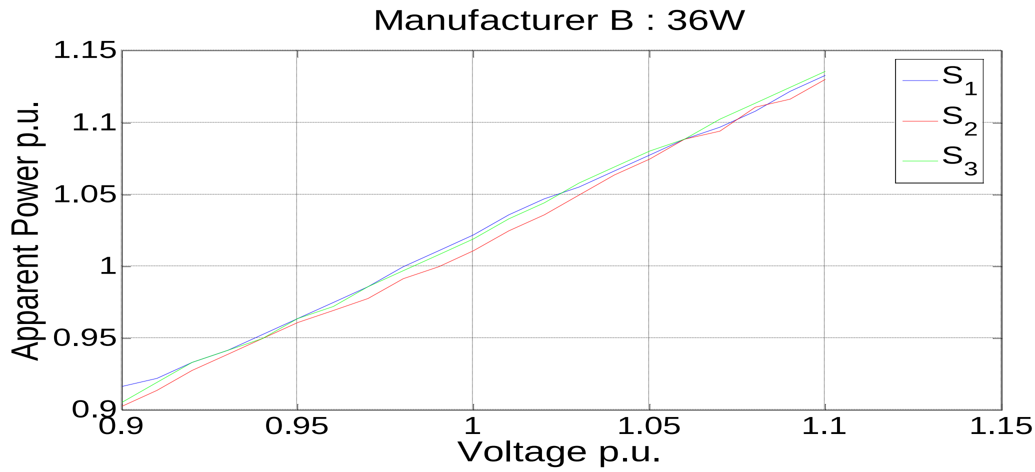

Figure 252: Apparent power versus RMS supply voltage for the three 36 W TFL samples from manufacturer B and electronic ballast alpha.

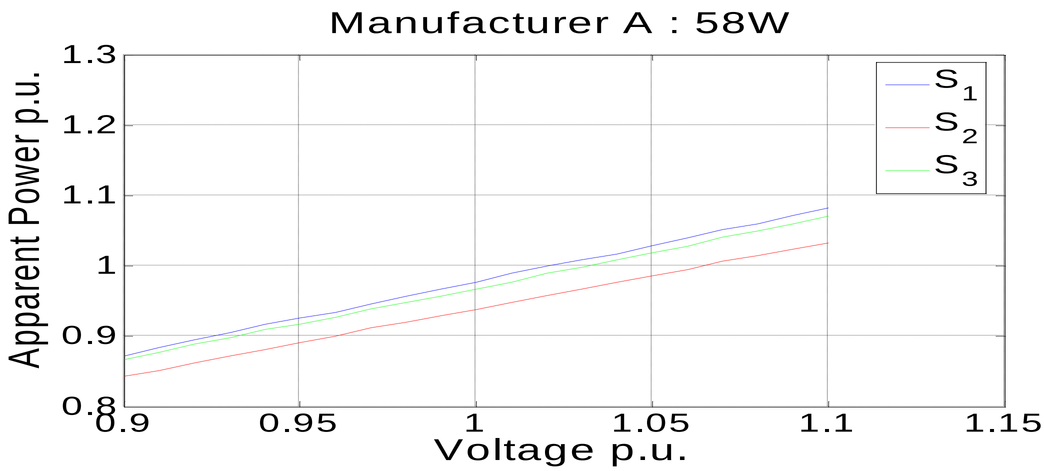

Figure 253: Apparent power versus RMS supply voltage for the three 58 W TFL samples from manufacturer A and electronic ballast alpha.

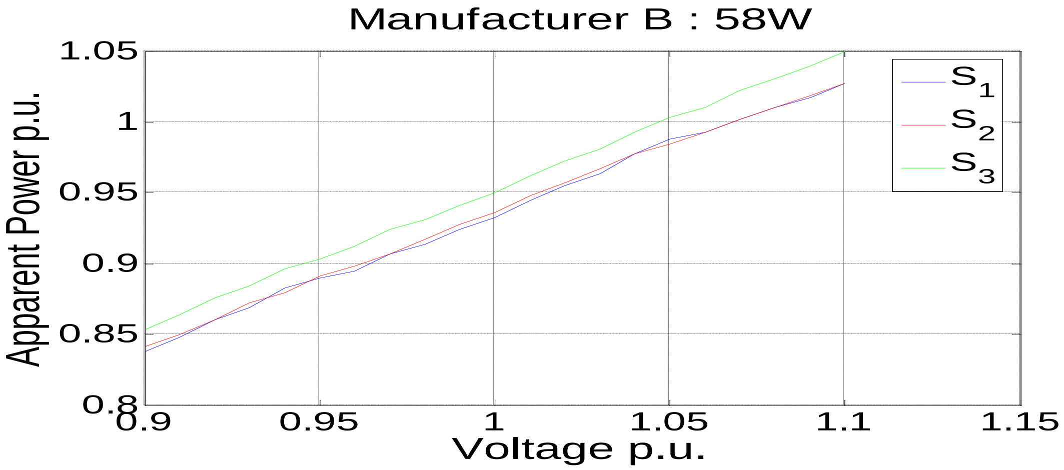

Figure 254: Apparent power versus RMS supply voltage for the three 58 W TFL samples from manufacturer B and electronic ballast alpha.

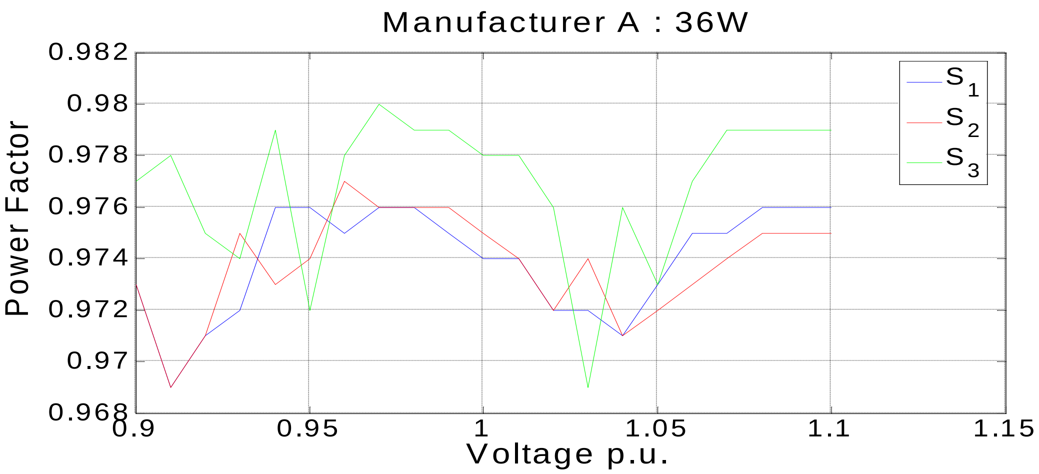

Figure 255: Power factor versus RMS supply voltage for the three 36 W TFL samples from manufacturer A and electronic ballast alpha.

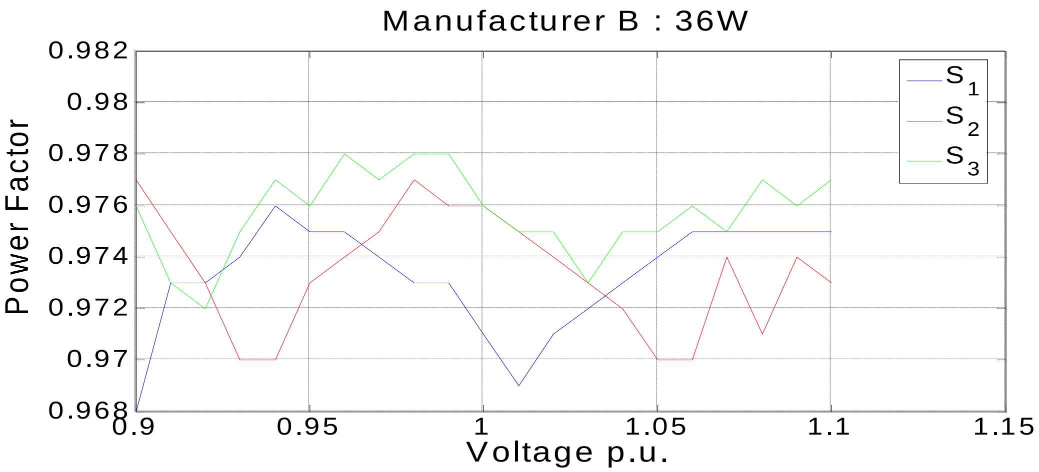

Figure 256: Power factor versus RMS supply voltage for the three 36 W TFL samples from manufacturer B and electronic ballast alpha.

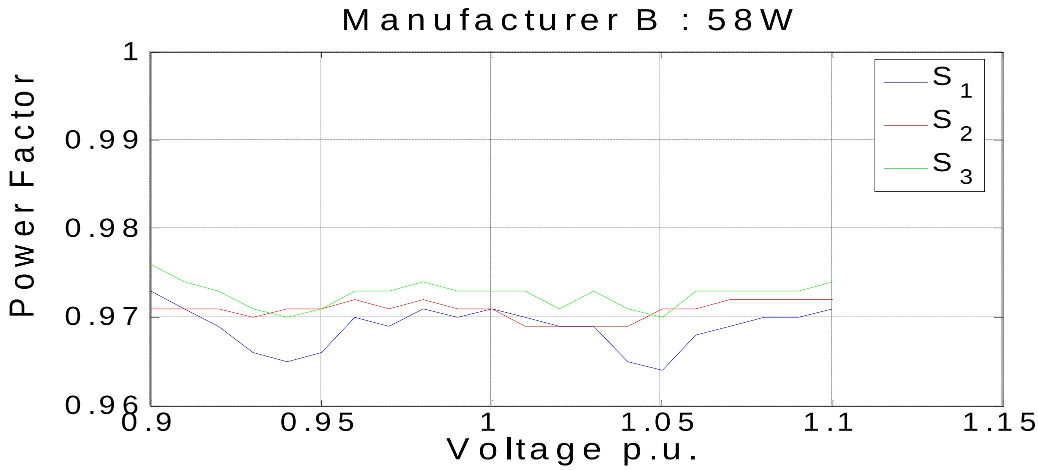

Figure 257: Power factor versus RMS supply voltage for the three 58 W TFL samples from manufacturer A and electronic ballast alpha.

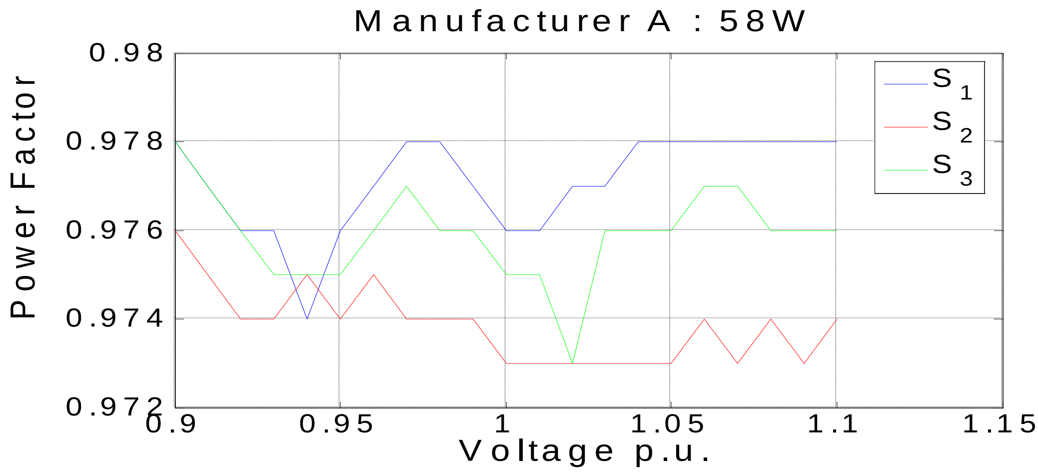

Figure 258: Power factor versus RMS supply voltage for the three 58 W TFL samples from manufacturer B and electronic ballast alpha.

A.5 Measurement results for High Intensity Discharge Lamps

Figure 259 and Figure 260 show the supply current as a function of the supply voltage for each of the samples (S_1, S_2, S_3) tested for the HIDL types listed in Table 18. The base value for the current is determined by equation B.1-1.

Figure 261 and Figure 262 show the active power consumption as a function of supply voltage for each of the samples tested for the HIDL types listed in Table 18. The base value for the active power is the rated power of the HIDL.

Figure 263 and Figure 264 show the reactive power consumption as a function of supply voltage for each of the samples tested for the HIDL types listed in Table 18. The base value for the reactive power is the rated power of the HIDL.

Figure 265 and Figure 266 show the apparent power consumption as a function of supply voltage for each of the samples tested for the HIDL types listed in Table 18. The base value for the apparent power is the rated power of the HIDL.

Figure 267 and Figure 268 show the power factor as a function of supply voltage for each of the samples tested for the HIDL types listed in Table 18. The HIDLs tested, have an inductive power factor.

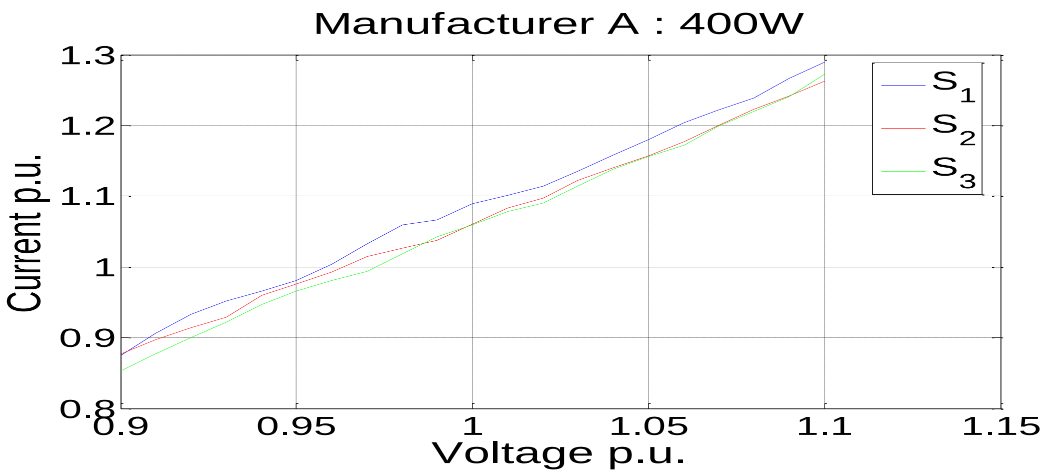

Figure 259: RMS supply current versus RMS supply voltage for the three 400 W HIDL samples from manufacturer A and magnetic ballast alpha.

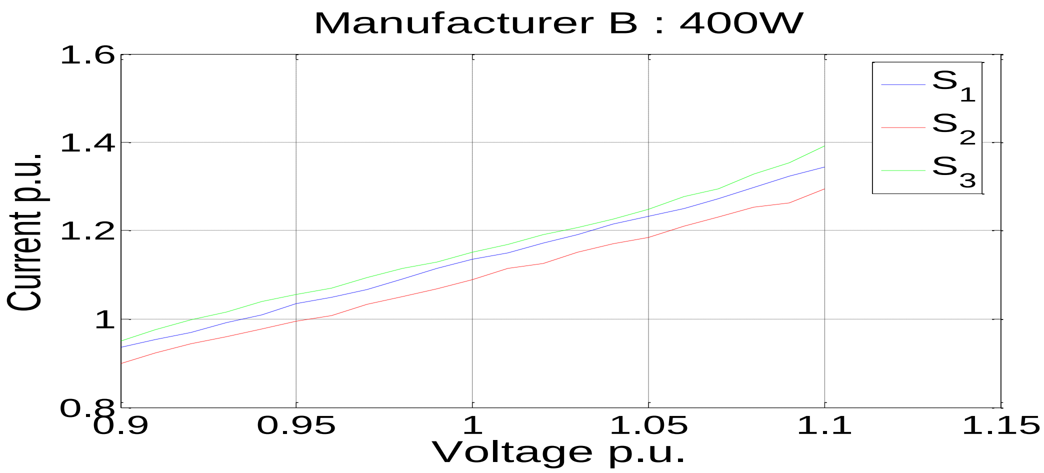

Figure 260: RMS supply current versus RMS supply voltage for the three 400 W HIDL samples from manufacturer B and magnetic ballast alpha.

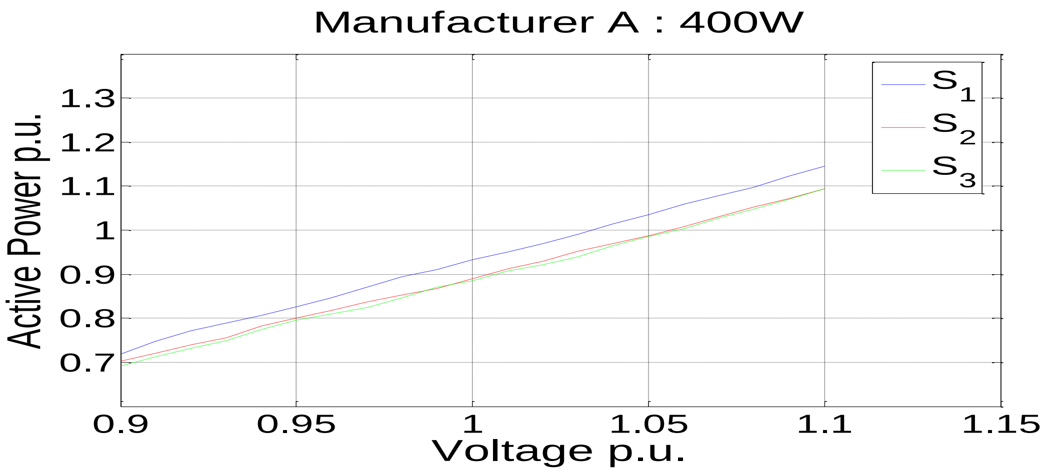

Figure 261: Active power versus RMS supply voltage for the three 400 W HIDL samples from manufacturer A and magnetic ballast alpha.

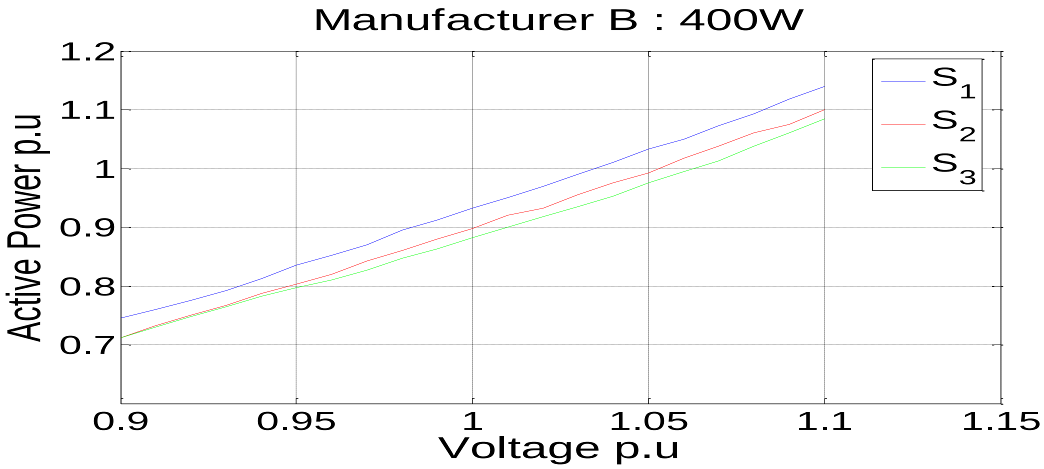

Figure 262: Active power versus RMS supply voltage for the three 400 W HIDL samples from manufacturer B and magnetic ballast alpha.

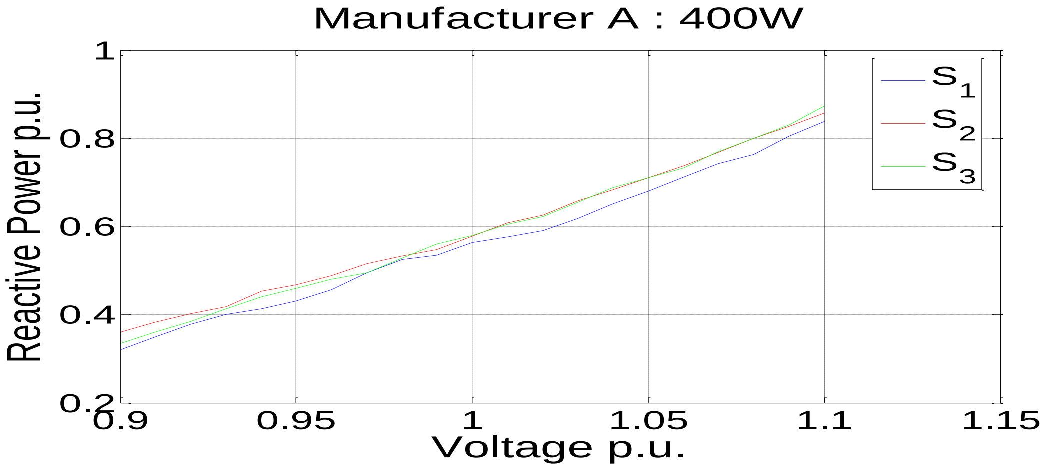

Figure 263: Reactive power versus RMS supply voltage for the 400 W HIDL samples from manufacturer A and magnetic ballast alpha.

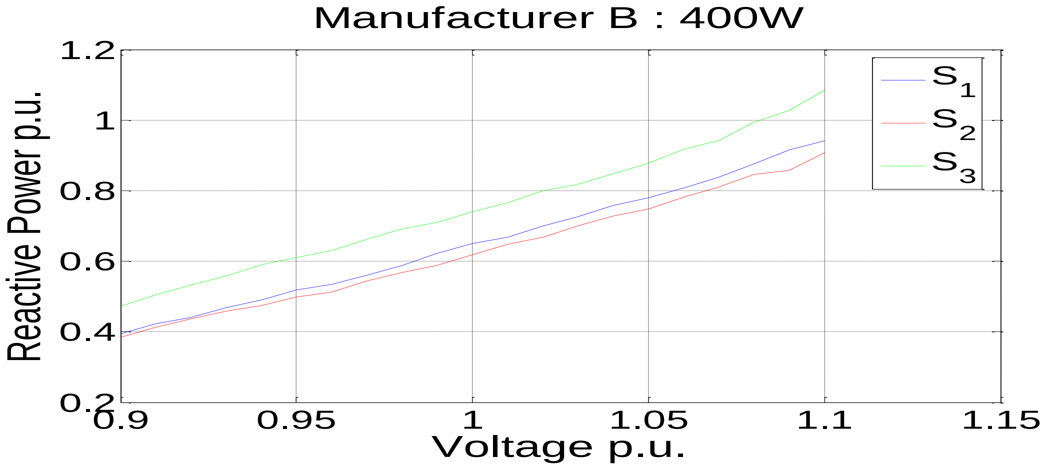

Figure 264: Reactive power versus RMS supply voltage for the three 400 W HIDL samples from manufacturer B and magnetic ballast alpha.

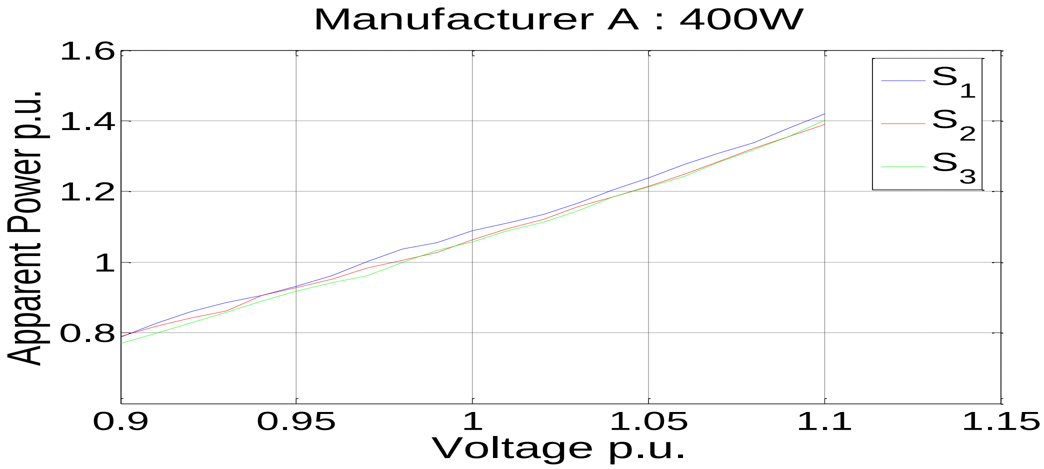

Figure 265: Apparent power versus RMS supply voltage for the three 400 W HIDL samples from manufacturer A and magnetic ballast alpha.

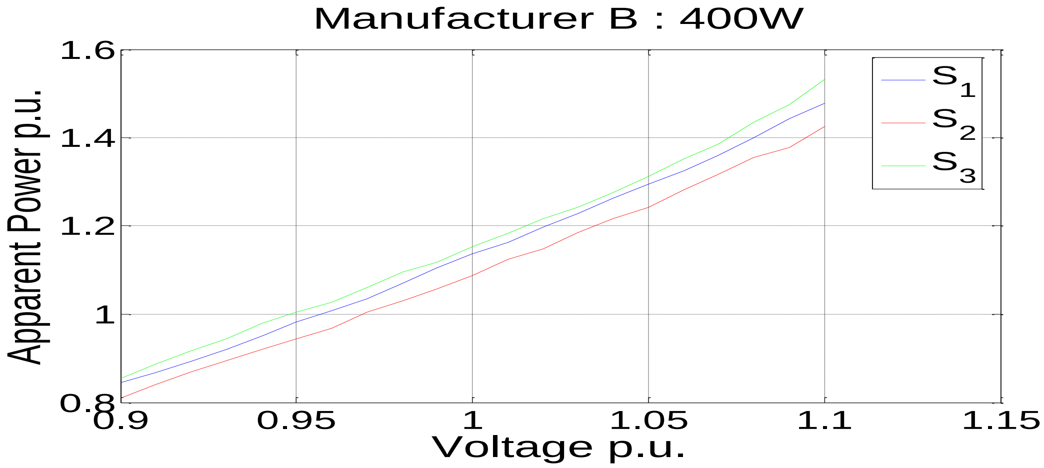

Figure 266: Apparent power versus RMS supply voltage for the three 400 W HIDL samples from manufacturer B and magnetic ballast alpha.

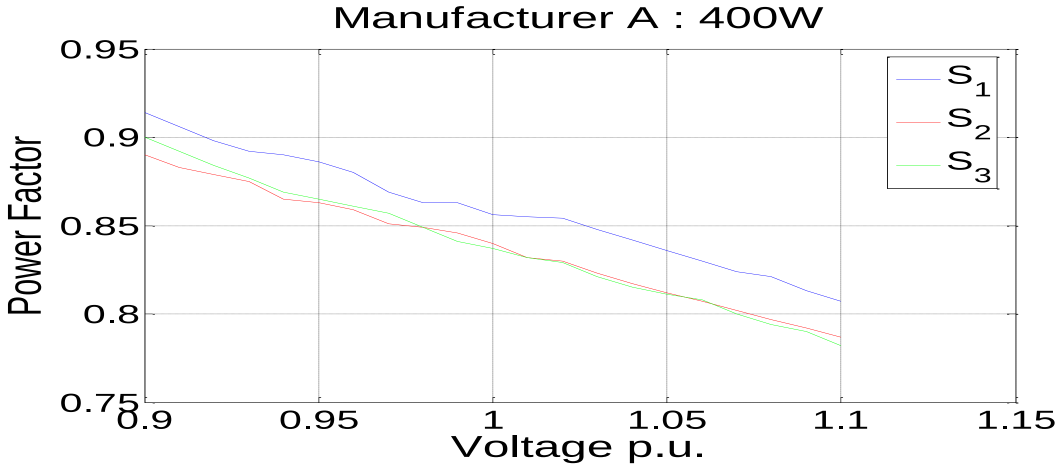

Figure 267: Power factor versus RMS supply voltage for the three 400 W HIDL samples from manufacturer A and magnetic ballast alpha.

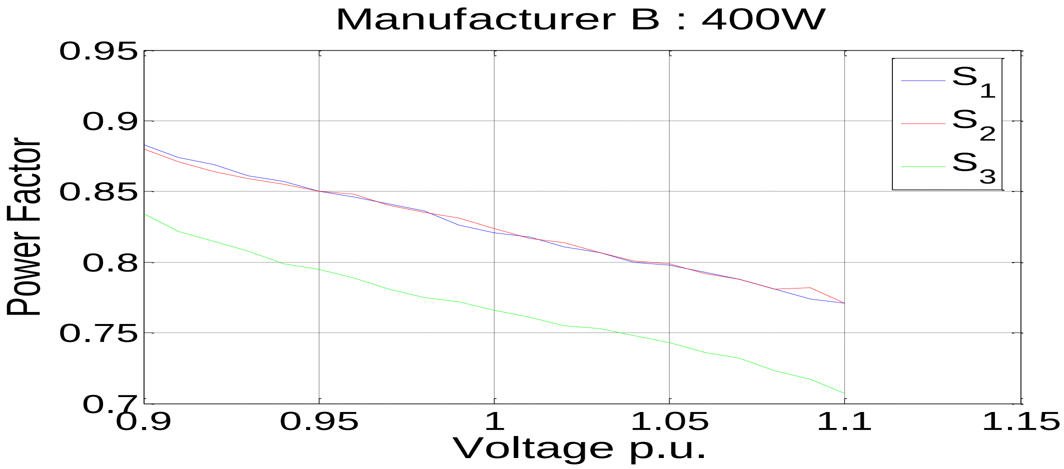

Figure 268: Power factor versus RMS supply voltage for the three 400 W HIDL samples from manufacturer B and magnetic ballast alpha.

Appendix B User's manual

This section contains a user's manual for the Lighting project software tool (LPST). The LPST works in conjunction with an SQL database.

B.1 Start

To start the program, run LPST.exe. Figure 269 shows the start page of the LPST. Click on the “Start” button. Figure 270 shows the “User information” page. Fill in the relevant details and click on the “Ok” button.

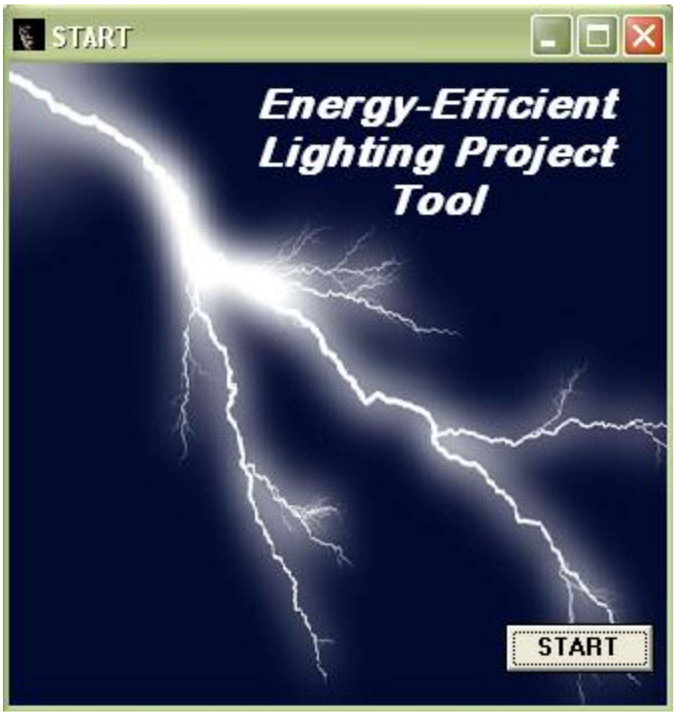

Figure 269: LPST start page.

Figure 270: User information page.

The “Main” page follows the “User information” page.

B.2 Main

Figure 271 shows what the “Main” page of the LPST looks like. The following functions and entries are performed on this page:

- The project number is entered.
- The lighting technologies for this project is selected and loaded.
- The calculation conditions are set.
- Group entries are displayed.
- File “open”, “save” and “export” functions are performed.
- The lighting technologies for this project is selected and loaded.

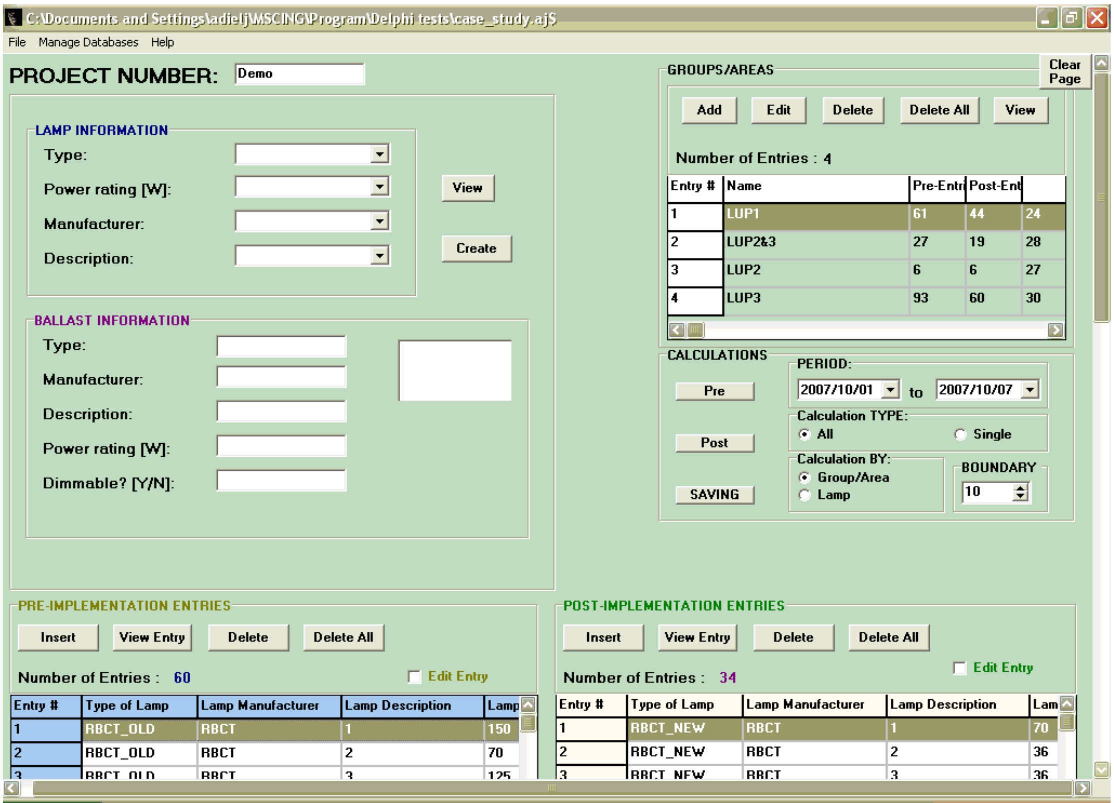

Figure 271: LPST main page

B.3 Creating a new lighting technology

Click on the “Create” button inside on the main page. Figure 272 shows the relevant page.

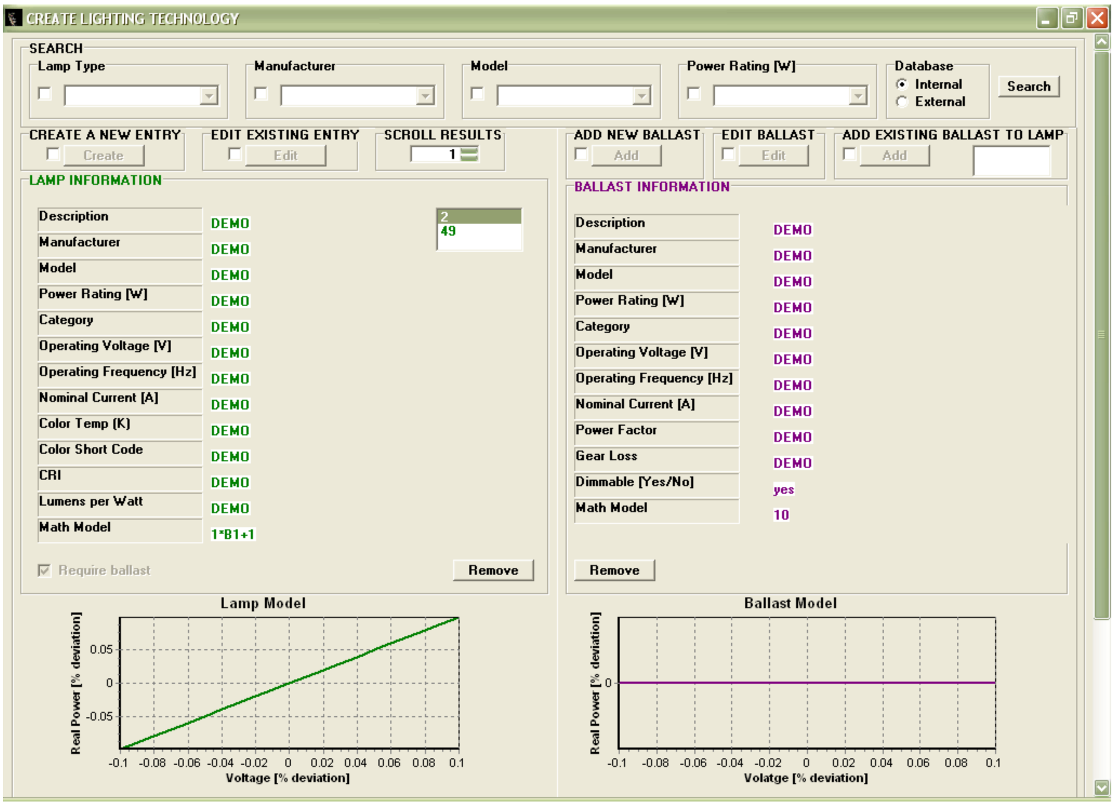

Figure 272: Create a lighting technology

The following functions are performed on this page:

- Create a new entry
- Search for existing lamps
- Edit an existing entry
- Create and assign a new ballast
- Edit an existing ballast
- Assign an existing ballast.

B.3.1 Create a new entry

To create a new lighting technology entry for your database, you must do the following:

- Click on the checkbox inside the "Create a new entry" box.
- Fill in the relevant details.
- If the lamp you are creating requires a ballast, click on the ballast checkbox, then fill in the relevant information for the ballast.
- Click the "Create" button next to the checkbox.

B.3.2 Search for existing lamps

To search your database, you must do the following:

- Click on the checkbox inside the box of the field you would like to search by. If none of the boxes are checked the search returns all the entries in your database.
- Fill in the condition for which you are searching.
- Click on the "Search" button.
- Use the scroll box to find the required entry.

B.3.3 Edit an existing entry

To create a new lighting technology entry for your database, you must do the following:

- Search for the required entry.
- Click on the checkbox inside the "Edit existing entry" box.
- Edit the relevant lamp and, if required, ballast details.
- Click the "Change" button next to the checkbox.

B.3.4 Create and assign a ballast

This function creates a new ballast which is stored in your database and then assigns it to an existing lamp. To create and assign a ballast, you must do the following:

- Search for the lamp to which the ballast is to be assigned.
- Click on the checkbox inside the "Edit ballast" box.
- Fill in the relevant information for the ballast.
- Click the "Change" button next to the checkbox.
-

B.3.5 Edit an existing ballast

Note: All the changes made using this function, except for changes made to the mathematical model, will be applied to all the lamps which utilize that specific ballast.

To edit an existing ballast, you must do the following:

- Search for the lamp to which the ballast is assigned.
- Click on the checkbox inside the "Add new ballast" box.
- If the lamp you are creating requires a ballast, click on the ballast checkbox, then fill in the relevant information for the ballast.
- Click the "Create" button.

B.3.6 Add existing ballast

To add an existing ballast, you must do the following:

- Click on the checkbox inside the “Add an existing ballast”.
- Choose form the list of available ballasts
- Click the “Add” button.

B.4 View a lighting technology

The following two types of lighting technologies can be viewed:

- Lighting technologies that exist within the database.
- Lighting technologies that are related to the specific project.

B.4.1 View lighting technology in within the database

- Select a lighting technology from the main page.
- Click on the “View” button.

B.4.2 View lighting technology related to the project

- Select a lighting technology from the pre-implementation or post-implementation entries grids.
- Click on the corresponding “View” button.

Figure 273 shows the resultant page.

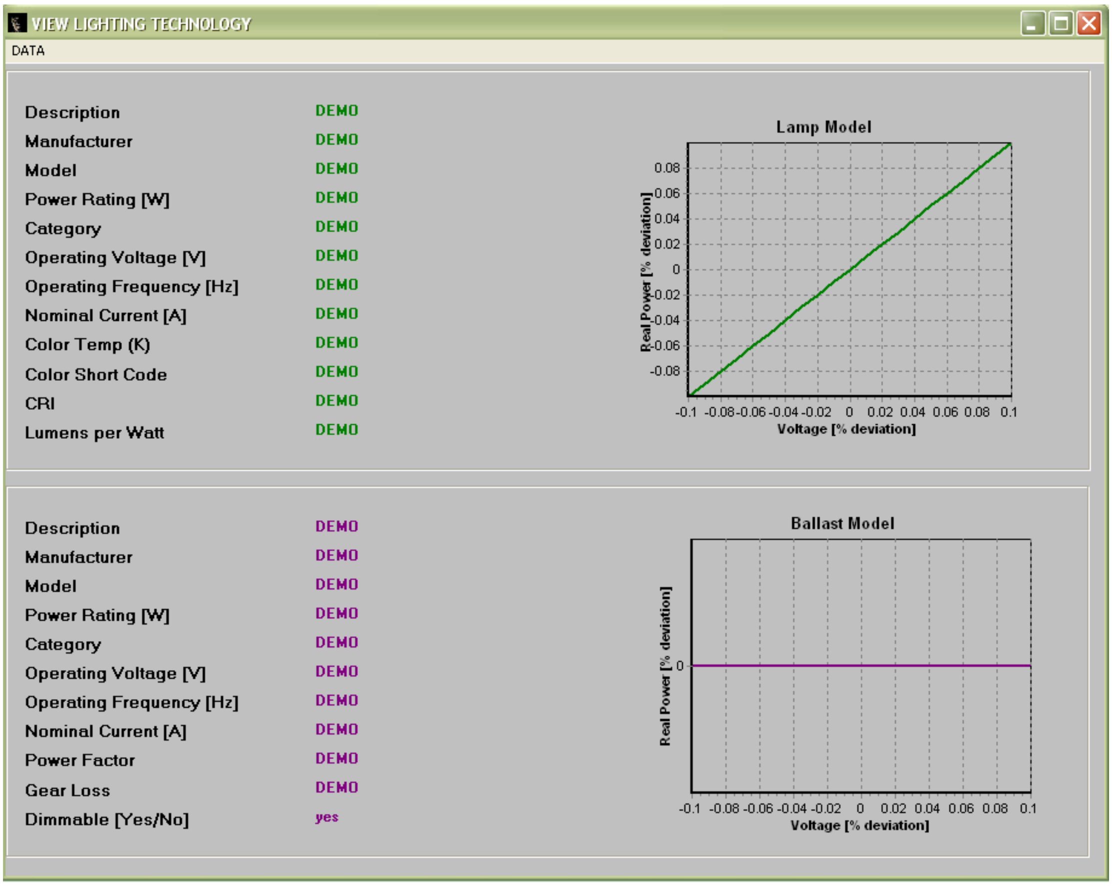

Figure 273: View lighting technology page.

B.5 Creating or Editing a group/sectional area

Click on either the “Add” button or select a group and click on the “Edit” button in the Groups/Areas box. Figure 274 shows the groups/areas page.

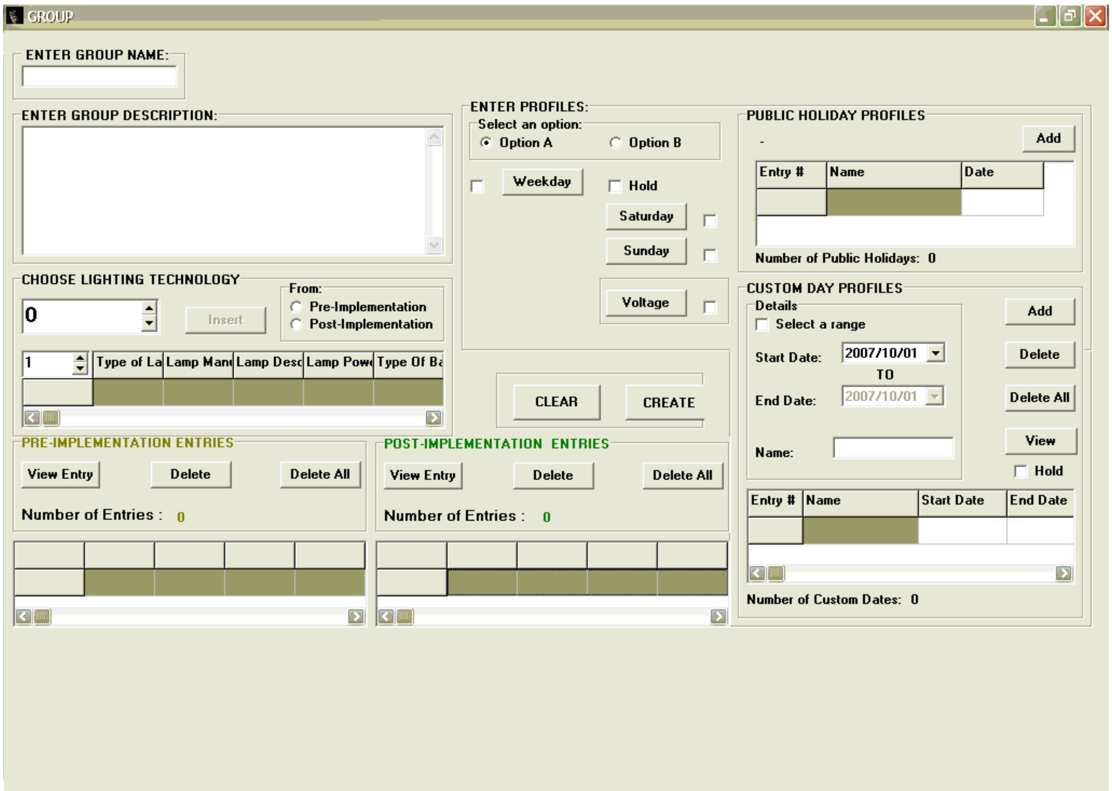

Figure 274: Groups/areas page.

B.5.1 Create or edit a group/area

Create or edit a group/area by doing the following:

- Enter/Edit the group/area name.
- Enter/Edit pre-implementation and/or post-implementation lighting technology entries.
    - Lighting technologies are selected from the pre-implementation and/or post-implementation entries grids on the “Main” page.
- Choose between selecting an average weekday (option A) and an individual weekday (option B) profile.
- Click on the selected day.
- Select a suitable profile from the “Profiles” page. (see chapter B.6)
- Click on the “Voltage” button and select a voltage profile for the group/area. (see chapter B.6)
- If applicable select a public holiday from the grid and add an artificial-light usage profile for that day. (see chapter B.6)
- If applicable create a condonable day/period and select an artificial-light usage profile for the selected day or period. (see chapter B.6)
- To view any of the selected profiles, click on the corresponding checkbox to the profile you want to see. In the case of the condonable days, select an entry then click on the “View” button. Figure 277 shows the “View profiles” page.

- Click on the “Create” or “Update” button.

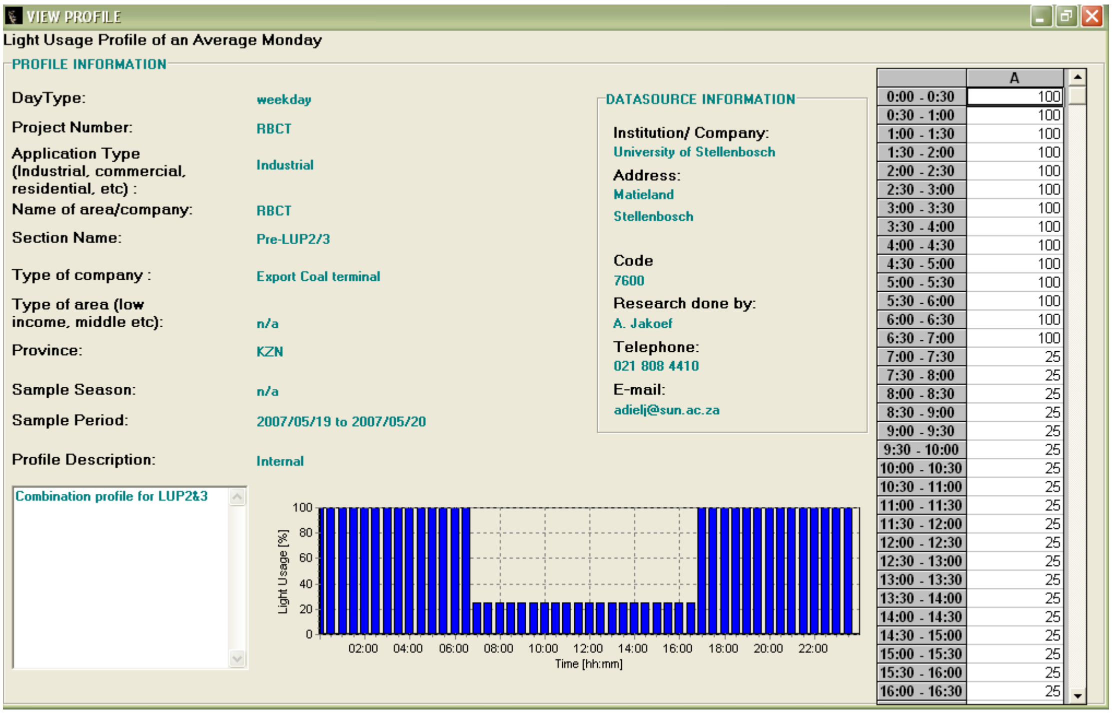

Figure 275: View profiles page.

B.5.2 View group/area

Select a group/area from the groups/areas grid on the “Main” page. Click on the corresponding “View” button. Figure 276 shows the “View groups/areas” page.

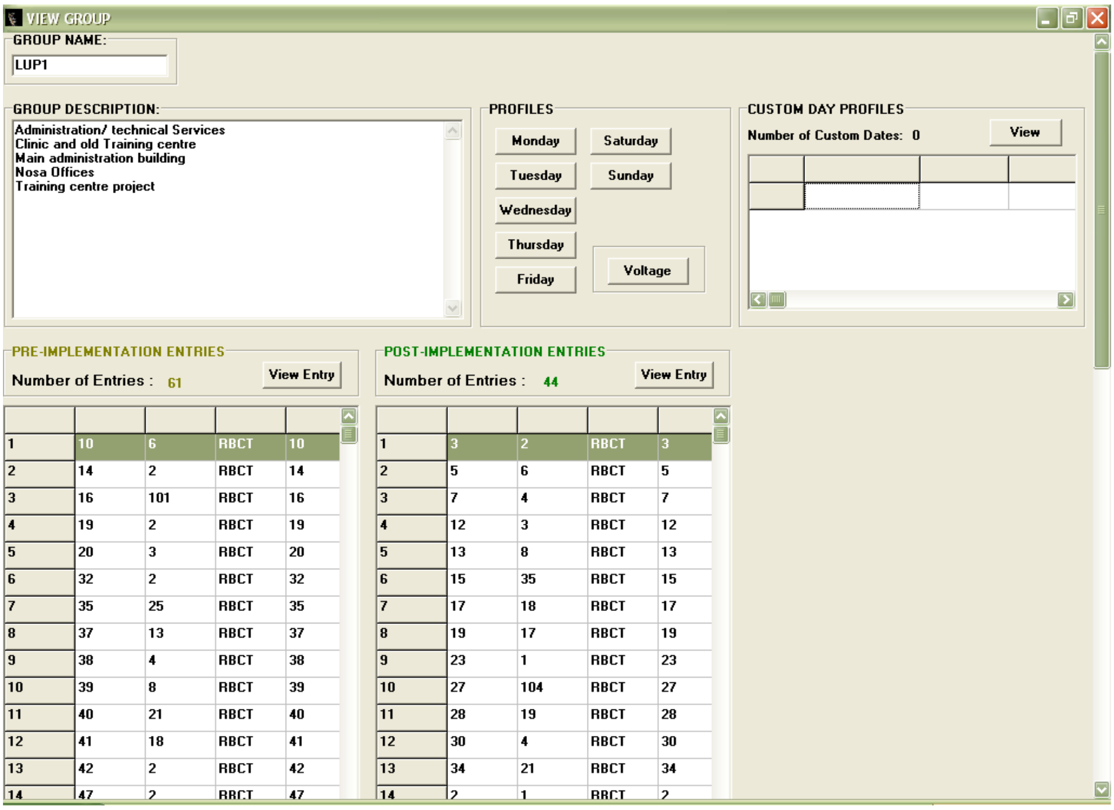

Figure 276: View group/area page.

To view the profiles selected for a group click on the corresponding button of the profile to be viewed.

B.6 Selecting/creating and editing voltage and artificial-light usage Profiles

From the groups/areas page, click on the button corresponding to the profile that is to be created. Figure 277 shows the "Profiles" page.

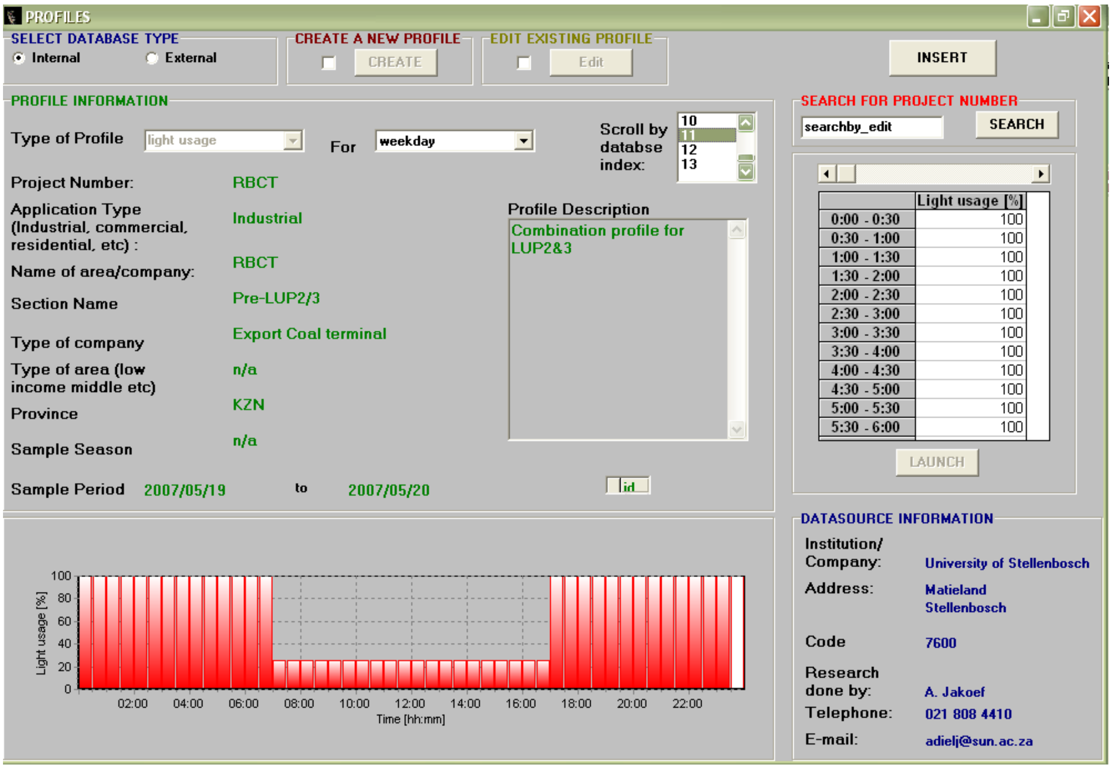

Figure 277: Profiles page.

The following functions are performed on this page:

- Create a new voltage or artificial-light profile.
- Search for existing voltage or artificial-light profile.
- Edit an existing voltage or artificial-light profile.

B.6.1 Create a new voltage or artificial-light profile

To create a voltage or artificial-light profile for your project, you must do the following:

- Select the "Internal" database option.
- Search for an existing profile, if a new profile is to be created based on an existing one. If not move to the following step.
- Click on the checkbox within the "Create a new profile" box.
- Fill in the relevant profile data.
- Click on the "Launch" button.
- Fill in the relevant profile data.
- Click on the "Create" button.

B.6.2 Search for existing voltage or artificial-light profile

To search your database for a specific profile, do the following:

- Select for the day type of the profile. The ID's of the resultant profiles will show in the scroll box.
- Scroll for the ID's for the desired profile.

or

- Enter the project name relevant to the desired profile. The ID's of the resultant profiles will show in the scroll box.
- Scroll for the ID's for the desired profile.

B.6.3 Edit an existing voltage or artificial-light profile

To edit an existing profile for your database, do the following:

- Select the "Internal" database option.
- Search for the desired profile. (see chapter B.6.2)
- Click on the checkbox within the "Edit existing profile" box.
- Fill in the relevant profile data.
- Click on the "Launch" button.
- Fill in the relevant profile data.
- Click on the "Edit" button.

Click o the "Insert" button to use a profile in the relevant group.

B.7 Calculated profile

On the "Main" page, enter the desired calculation parameters, i.e. profile period, type of calculation etc. If a valid project parameters and information has been entered, click the button corresponding to the calculation that is to be done. Figure 278 shows the calculation profile page.

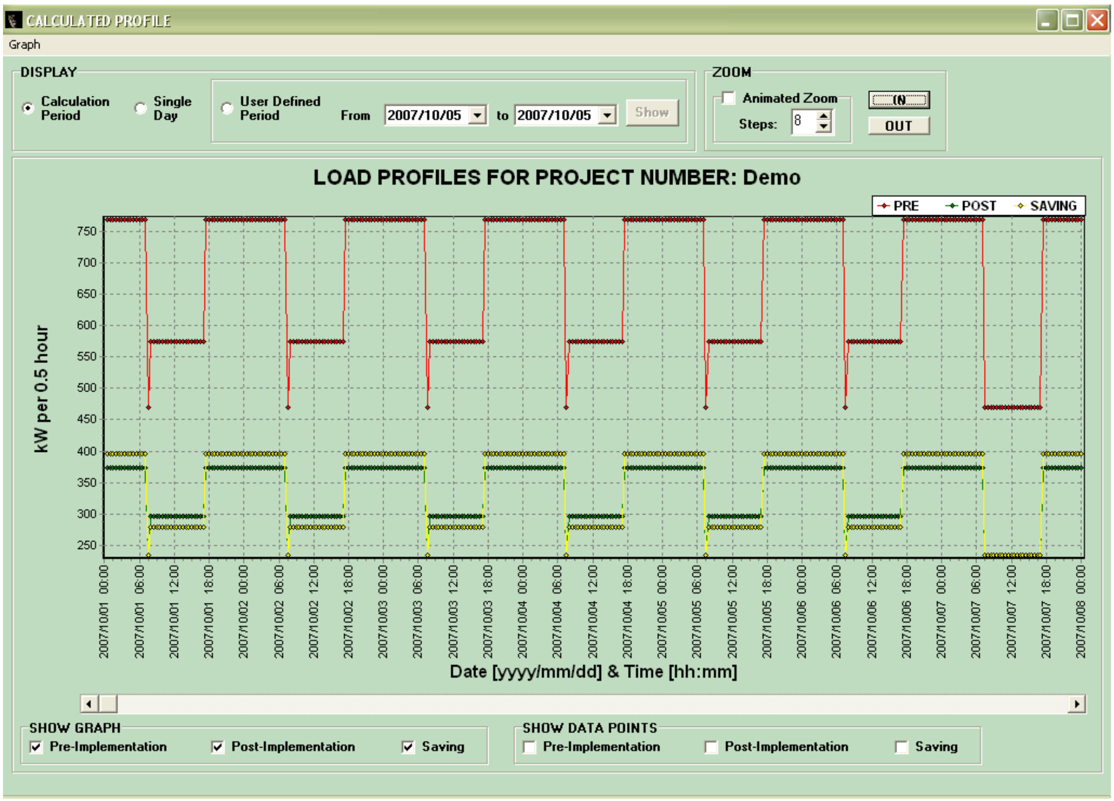

Figure 278: Calculated profiles page.

The following functions are performed on this page:

- Display calculation results.
- View user defined extracts of the results.
- Zoom in and out of graph.
- View data points.
- Select results to be viewed.
- Save as a bitmap picture (.bmp).
- Export data to Microsoft excel.

B.7.1 Viewing periods

The calculation results can be viewed for the following periods:

- The user defined calculation period.
    - Select the relevant check box.
- One day.
    - Select the relevant check box.
- A user defined period within the calculation period.
    - Select the relevant check box.

- Enter a valid period to be viewed.
- Click on the “Show” button.

B.7.2 Viewing graphs and data points

This function allows the user to select which results are to be viewed. The user also selects whether or not data points is to be viewed.

- Click on the relevant checkbox within the “Show graphs” and “Show data points” boxes.

B.7.3 Zoom

This function allows the user to zoom in or out of the graph.

- To zoom in or out click on the relevant button.
- Select animated zoom, to view animated zoom in user defined steps.
- Select the animated zoom steps by editing the relevant scroll box.

B.7.4 Save as a bitmap picture (.bmp)

This function stores the graph as a .bmp file.

- Click on “Graph” and select the “save” function.
- Follow the prompts.

B.7.5 Export data to Microsoft excel

This function stores the data points of the graph as a .xls file.

- Click on “Graph” and select the “Export” function.
- Follow the prompts.

B.8 File “open”, “save” and “export”

These functions load and store project cases. The option to export all the case information to a Microsoft Excel format also exists.

- Click on “File” then select the “Save”, “Save as”, “Load” or “Export” as desired.
- Follow the prompts.

Appendix C Case study data

Table 29: Summary of pre-implementation lighting load as supplied by the ESCO [23].

Lamp ID	Description	Lamp Power [W]	# Lamps	Power Factor	Total Luminiare Power (incl. gear losses) [W]	Total number of Fittings	Total kW Load	Total kVar	Total kVA
1	Industrial Bulkhead - magnetic chokes-	150	1	0.900	160	170	27.200	13.174	30.222
2	Industrial Bulkhead - magnetic chokes-	70	1	0.900	78	897	69.966	33.886	77.740
3	Industrial Bulkhead - magnetic chokes-	125	1	0.900	128	3014	385.792	186.848	428.658
4	Industrial Bulkhead - magnetic chokes-	80	1	0.900	82	588	48.216	23.352	53.573
5	HPS 250w Flood Light- magnetic chokes-	250	1	0.900	255	30	7.650	3.705	8.500
6	Industrial Bulkhead - magnetic chokes-	250	1	0.900	255	65	16.575	8.028	18.417
7	MV 250w Flood Light- magnetic chokes-	250	1	0.900	250	8	2.000	0.969	2.222
8	L Bay open- magnetic chokes-	400	1	0.900	410	11	4.510	2.184	5.011
9	H Bay M.beam - magnetic chokes-	1000	1	0.900	1000	13	13.000	6.296	14.444
10	Open Channel -cool white magnetic chokes-	58	2	0.900	124	7	0.868	0.420	0.964
11	'Bulkhead 60 w inc. Luminaires---	60	1	1.000	60	1	0.060	0.000	0.060
12	Open Channel T8 wingscool white magnetic chokes-	75	2	0.850	120	3	0.360	0.223	0.424
13	Open Channel cool white magnetic	75	2	0.850	120	16	1.920	1.190	2.259

	chokes-								
14	Decor. surf. mount. Econocool white magnetic chokes-	36	2	0.900	84	88	7.392	3.580	8.213
15	Decor. surf. mount. Econocool white magnetic chokes-	65	2	0.850	130	1	0.130	0.081	0.153
16	Decor. surf. mount. Econocool white magnetic chokes-	58	2	0.900	124	170	21.080	10.210	23.422
17	Rec. FL decor Aluminium framecool white magnetic chokes-	18	4	0.900	84	298	25.032	12.124	27.813
18	H Bay M.beam-magnetic chokes-	400	1	0.900	410	11	4.510	2.184	5.011
19	D Proof polyc.cool white magnetic chokes-	36	2	0.900	84	71	5.964	2.888	6.627
20	D Proof polyc.cool white magnetic chokes-	58	1	0.900	62	5	0.310	0.150	0.344
21	HPS 70w Flood Light- magnetic chokes-	70	1	0.900	78	109	8.502	4.118	9.447
22	HPS 150w Flood Light- magnetic chokes-	150	1	0.900	160	21	3.360	1.627	3.733
23	HPS 400w Flood Light- magnetic chokes-	400	1	0.900	420	162	68.040	32.953	75.600
24	MV 125w Flood Light- magnetic chokes-	125	1	0.900	128	137	17.536	8.493	19.484
25	MV 400w Flood Light- magnetic chokes-	400	1	0.900	410	2	0.820	0.397	0.911

26	Rec. FL decor Aluminium frame - U lampcool white magnetic chokes-	40	2	0.850	91	106	9.646	5.978	11.348
27	Rec. FL decor Aluminium framecool white magnetic chokes-	36	2	0.900	84	35	2.940	1.424	3.267
28	Electr. Lamp 20W 220V long lifeCool whiteECG / CFL-	20	1	0.550	20	8	0.160	0.243	0.291
29	DL + 50w 12V & Transformer-Magnetic tranf.-	50	1	0.980	65	35	2.275	0.462	2.321
30	Rec. FL decor Aluminium framecool white magnetic chokes-	18	3	0.900	63	1	0.063	0.031	0.070
31	60 w inc. Luminaires---	60	1	1.000	60	27	1.620	0.000	1.620
32	100 w inc. Luminaires---	100	1	1.000	100	13	1.300	0.000	1.300
33	H Bay M.beam-magnetic chokes-	400	1	0.900	420	7	2.940	1.424	3.267
34	Reces FL LBR. 12 bladescool white magnetic chokes-	40	2	0.850	91	14	1.274	0.790	1.499
35	PL Luminaires 2x 9w- magnetic chokes-	9	2	0.700	26	54	1.404	1.432	2.006
36	Bulkhead Luminaires 2x 9w-magnetic chokes-	9	2	0.700	26	3	0.078	0.080	0.111
37	Rec. FL decor Aluminium framecool white magnetic chokes-	36	3	0.900	126	16	2.016	0.976	2.240

38	Rec. FL decor Aluminium framecool white magnetic chokes-	36	4	0.900	168	6	1.008	0.488	1.120
39	Reces FL LBR. 5 bladescool white magnetic chokes-	18	4	0.900	84	9	0.756	0.366	0.840
40	Reces FL LBR. 12 bladescool white magnetic chokes-	36	3	0.900	126	58	7.308	3.539	8.120
41	Reces FL LBR. 12 bladescool white magnetic chokes-	36	4	0.900	168	40	6.720	3.255	7.467
42	Reces FL LBR. 14 bladescool white magnetic chokes-	58	2	0.900	124	2	0.248	0.120	0.276
43	D Proof polyc.cool white magnetic chokes-	58	2	0.900	124	2	0.248	0.120	0.276
44	Open Channel cool white magnetic chokes-	40	1	0.850	45.5	2	0.091	0.056	0.107
45	Open Channel cool white magnetic chokes-	40	2	0.850	91	22	2.002	1.241	2.355
46	Reces FL LBR. 12 bladescool white magnetic chokes-	36	2	0.900	84	1	0.084	0.041	0.093
47	Open Channel cool white magnetic chokes-	65	1	0.850	65	11	0.715	0.443	0.841
48	Open Channel cool white magnetic chokes-	65	2	0.850	130	78	10.140	6.284	11.929
49	PL Luminaires 11w-magnetic chokes-	11	1	0.800	16	4	0.064	0.048	0.080
50	Decor. surf. mount. Econocool white	40	1	0.850	45.5	16	0.728	0.451	0.856

	magnetic chokes-								
51	Decor. surf. mount. Econocool white magnetic chokes-	40	2	0.850	91	6	0.546	0.338	0.642
52	PL Luminaires 13w-magnetic chokes-	13	1	0.850	18	4	0.072	0.045	0.085
53	Decor. surf. mount. Econocool white magnetic chokes-	18	4	0.900	84	10	0.840	0.407	0.933
54	Reces FL LBR. 5 bladescool white magnetic chokes-	18	3	0.900	63	12	0.756	0.366	0.840
55	D Proof polyc.cool white magnetic chokes-	40	1	0.850	45.5	3	0.137	0.085	0.161
56	D Proof polyc.cool white magnetic chokes-	40	2	0.850	91	776	70.616	43.764	83.078
57	D Proof polyc.cool white magnetic chokes-	65	1	0.850	65	38	2.470	1.531	2.906
58	D Proof polyc.cool white magnetic chokes-	65	2	0.850	130	34	4.420	2.739	5.200
59	Reces FL LBR. 12 bladescool white magnetic chokes-	40	3	0.850	136.5	71	9.692	6.006	11.402
60	SUrface FL LLB Louvrecool white magnetic chokes-	40	4	0.850	182	1	0.182	0.113	0.214
Total						7423	886.351	443.765	991.234

Table 30 Summary of post-implementation lighting load as supplied by the ESCO [23].Lamp ID	Description	Lamp Power [W]	Number of lamps	Power Factor	Total Luminiare Power (incl. gear losses) [W]	Total number of Fittings	Total kW Load	Total kVar	Total kVA
1	HQI 70w ALUMINIUM Flood Light- magnetic chokes	70	1	0.9	96	137	13.152	6.370	14.613
2	Open Channel -cool day light ECG	36	1	0.96	35	2	0.070	0.020	0.073
3	Open Channel -Cool DAY white ECG	36	1	0.96	35	33	1.155	0.337	1.203
4	Open Channel -Cool DAY white ECG	36	2	0.96	70	19	1.330	0.388	1.385
5	Open Channel -Cool DAY white ECG	58	1	0.96	55	85	4.675	1.364	4.870
6	Open Channel -Cool DAY white ECG	58	2	0.96	110	88	9.680	2.823	10.083
7	Retrofit + Triph Lamp/s Cool DAY white ECG	36	3	0.96	105	6	0.630	0.184	0.656
8	HQI 150w Aluminium Flood Light- magnetic chokes	150	1	0.9	169.5	6	1.017	0.493	1.130
9	D Proof polyc.Cool DAY white ECG	58	2	0.96	110	14	1.540	0.449	1.604
10	D Proof polyc.Cool DAY white ECG	36	1	0.96	35	30	1.050	0.306	1.094
11	D Proof polyc.Cool DAY white ECG	58	1	0.96	55	2	0.110	0.032	0.115
12	Retrofit + Triph Lamp/s with 2x springs and 2x cap L/holderCool DAY white ECG	36	1	0.96	35	43	1.505	0.439	1.568
13	Retrofit + Triph Lamp/sCool DAY white	18	3	0.96	62.4	9	0.562	0.164	0.585

	ECG								
14	Retrofit + Triph Lamp/s plus 1200x600 perspex (remove LBR and substitute with new Pespex)Cool DAY white ECG	36	2	0.96	70	94	6.580	1.919	6.854
15	Decor. surf. mount. Econocool white magnetic chokes	18	4	0.9	84	10	0.840	0.407	0.933
16	Retrofit existing D/L with IRC lamp & electronic Transf. and New Lamp Holder- Electronic Transf	35	1	0.99	38	35	1.330	0.190	1.343
17	Retrofit + Triph Lamp/scool day light ECG	36	1	0.96	35	19	0.665	0.194	0.693
18	Retrofit + Triph Lamp/scool day light ECG	36	2	0.96	70	36	2.520	0.735	2.625
19	Retrofit + Triph Lamp/sCool DAY white ECG	36	2	0.96	70	34	2.380	0.694	2.479
20	Retrofit + Triph Lamp/s with 6 x springs and 6 x cap L/holderCool DAY white ECG	18	3	0.96	62.4	106	6.614	1.929	6.890
21	HQI 250w Aluminium Flood Light- magnetic chokes	250	1	0.9	284.2	1	0.284	0.138	0.316
22	Retrofit + Triph Lamp/scool day light ECG	18	3	0.96	54	311	16.794	4.898	17.494
23	Retrofit + B40 to a Dulux 1x42w T/E- ECG	42	1	0.98	45	4669	210.105	42.664	214.393

24	Retrofit 3x36w as 2x36w with Triph Lamp/s plus 1200x200 Perspex to blind middle lampCool DAY white ECG	36	2	0.96	70	72	5.040	1.470	5.250
25	Retrofit 250W HQI for Flood - Bulk ONLY-magnetic chokes	250	1	0.9	284.2	2	0.568	0.275	0.632
26	Retrofit 150W HQI for Flood - Bulk ONLY-magnetic chokes	150	1	0.9	169.5	97	16.442	7.963	18.268
27	Retrofit + Triph Lamp/s with 4 x springs and 4 x cap L/holderCool DAY white ECG	36	2	0.96	70	209	14.630	4.267	15.240
28	Retrofit + Triph Lamp/sCool DAY white ECG	36	1	0.96	35	909	31.815	9.279	33.141
29	Electr. Lamp 15W 220V long lifeCool whiteECG / CFL	15	1	0.55	15.5	28	0.434	0.659	0.789
30	Electr. Lamp 20W 220V long lifeCool whiteECG / CFL	20	1	0.55	20	23	0.460	0.699	0.836
31	vENTURA LAMP 70Whqi FOR hps GEAR elliptical-magnetic chokes	70	1	0.9	96	109	10.464	5.068	11.627
32	vENTURA LAMP 150W hqi FOR hps GEAR elliptical- magnetic chokes	150	1	0.9	169.5	21	3.560	1.724	3.955
33	HPS 400w Flood Light-magnetic chokes	400	1	0.9	420	161	67.620	32.750	75.133
34	PL Luminaires 2x 9w-magnetic chokes	9	2	0.7	26	50	1.300	1.326	1.857
Total						7470	436.921	132.616	456.603

Table 31: Sectional area key for use with

Table 32 and Table 33

Code	Area	Code	Area	Code	Area
A	Admin/ Technical services	I	Canteen	Q	Belt motors
B	Radio tower	J	All conveyors	R	Substation & Transformer Rooms
C	Carport/ parking tech services	K	All transfer towers	S	Stackers/ Reclaimers
D	Tippler/ship loader w/shop	L	Dockside fencing lights	T	NOSA Offices
E	Site cleaning w/shop	M	Ship loaders/wharf conveyors	U	Training Centre Project
F	Clinic & old training centre	N	Tipplers	V	Yard Machine Workshop
G	Main admin building	O	All pole lights	W	Miscellaneous areas
H	Gate house	P	Wharf transfer towers/ buildings		

Table 32: Pre-implementation lighting technologies survey as supplied by the ESCO [23].

Lamp ID	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	0	0	0	0	3	0	0	0	0	109	9	0	12	5	0	0	0	3	29	0	0	0	0
2	0	0	0	0	0	5	0	0	0	367	3	0	377	0	0	35	16	31	63	0	0	0	0
3	0	0	0	0	7	11	0	3	0	1524	278	0	140	52	82	21	175	33	617	0	0	1	70
4	0	0	0	0	0	0	0	0	0	7	0	0	581	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	16	0	0	0	0	1	1	11	0	0	0	0	0	1
6	0	0	0	0	0	0	0	0	0	65	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	6	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	3	0	0	0	8	0	0	0	0	0	0	0	0	0
9	0	0	0	8	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0
10	6	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0
14	2	0	0	2	21	15	0	0	3	14	0	0	0	4	0	0	0	0	0	0	0	27	0
15	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	101	0	0	0	0	54	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0
17	0	0	0	0	12	0	250	0	0	0	0	0	0	0	0	0	0	0	0	36	0	0	0
18	0	0	0	2	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0
19	2	0	0	0	13	9	1	2	20	0	0	0	0	2	0	0	0	6	14	0	0	2	0
20	3	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	109	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	20	0	0	0	0
23	0	0	0	1	2	0	0	0	0	25	10	0	41	73	0	0	0	10	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	54	16	0	0	0	0	0	0	0	67	0	0	0	0
25	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0
27	0	0	0	4	0	0	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

28	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	17	1	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	17	0	6	0	0
32	2	2	0	0	0	0	2	0	0	0	1	0	0	4	0	0	0	0	0	0	2	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	4	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0
35	25	7	11	1	0	2	0	0	0	7	0	0	0	0	0	0	0	1	0	0	0	0	0
36	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
37	13	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	4	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	21	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29	0	0
41	18	0	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
44	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
45	0	0	0	2	0	3	6	0	0	0	0	0	0	0	0	0	0	2	0	9	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
47	2	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
48	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	76	0	0	0	0	0
49	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0
55	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	9	1	1	23	22	99	7	13	22	137	76	0	0	23	0	25	30	117	132	1	5	27	6
57	0	0	0	0	0	0	0	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	1	0	0	0	0	0	0	26	2	5	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	71	0	0

60	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	244	27	18	45	85	201	443	87	91	2351	393	109	1151	176	83	82	232	304	963	53	142	66	77

Table 33: Post-implementation lighting technologies survey as supplied by the ESCO [23].

Lamp ID	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	0	0	0	0	0	0	0	0	0	54	16	0	0	0	0	0	0	0	67	0	0	0	0
2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3	2	0	6	2	0	3	6	0	0	0	0	0	0	0	0	0	0	5	0	9	0	0	0
4	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0
5	6	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	76	0	0	0	0	0
6	0	0	0	36	0	0	0	0	0	38	0	0	0	6	0	0	0	0	8	0	0	0	0
7	4	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	6	0	0	0	8	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
12	3	0	0	0	0	0	0	38	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	35	8	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	29	0	0
15	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	17	1	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	18	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	4	0	0	31	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
19	17	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	14	0	0
20	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
22	0	0	0	0	12	0	251	0	0	0	0	0	0	0	0	0	0	0	0	36	12	0	0
23	0	0	0	0	10	16	0	3	0	2007	290	0	1110	57	82	56	191	67	709	0	0	1	70
24	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	71	0	0
25	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	83	0	0	0	0	1	1	11	0	0	0	0	0	1
27	104	0	0	0	0	54	5	29	2	5	0	0	0	0	0	0	0	0	0	0	2	8	0

28	19	1	1	25	56	123	8	15	45	151	76	0	0	29	0	25	30	93	144	1	5	56	6
29	0	0	0	2	1	0	2	0	0	0	0	0	0	0	0	0	0	0	17	0	6	0	0
30	4	10	0	0	0	0	2	0	0	0	1	0	0	4	0	0	0	0	0	0	2	0	0
31	0	0	0	0	0	0	0	0	0	0	0	109	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	20	0	0	0	0
33	0	0	0	1	2	0	0	0	0	24	10	0	41	73	0	0	0	10	0	0	0	0	0
34	21	7	11	1	0	2	0	0	0	7	0	0	0	0	0	0	0	1	0	0	0	0	0
Total	242	27	18	71	85	201	434	87	91	2378	393	109	1151	179	83	82	232	303	967	52	142	66	77